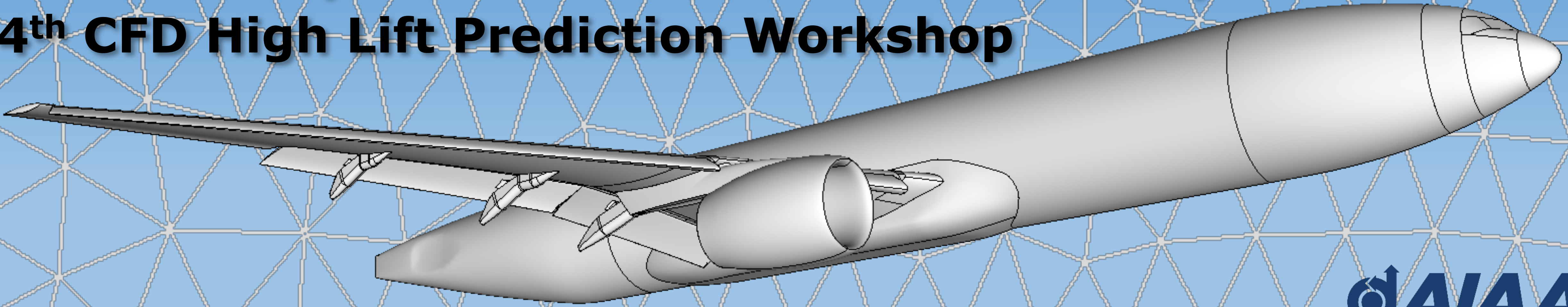
3rd Geometry and Mesh Generation Workshop
4th CFD High Lift Prediction Workshop



SHAPING THE FUTURE OF AEROSPACE

Committee Summary

GMGW / HLPW Leadership Team

Introduction

- We performed independent analysis of all data (across all TFGs)
  - Looking for trends
  - Attempting to be as objective as possible
  - We formed our own high-level Key Questions (KQs) and tried to answer them using the submitted data
  - We focused primarily on the “BEST PRACTICE” results submitted
- This analysis is preliminary: final analysis will be presented at a summary paper for AIAA Aviation 2022
- This talk leads directly into Open Discussion

TFG Labeling

- **G:** Geometry & Mesh preparation (GEOM TFG)
- **R:** Fixed-mesh RANS (RANS TFG)
- **A:** Mesh adaptation for RANS (ADAPT TFG)
- **H:** High-order discretization (HO TFG)
- **L:** Hybrid RANS-LES (HRLES TFG)
- **W:** Wall-modeled LES and Lattice-Boltzmann (WMLESLB TFG)

Committee KQs

#	Key Question
1	What CFD solution methodology(ies) currently provides the **best/most-consistent approach** to predicting (a) increments due to flap deflection, and (b) maximum lift?
2	What are important **lessons learned** in high-lift CFD analysis explored in HLPW-4?
3	What **geometry and meshing best practices** are appropriate for high-lift CFD analysis for RANS, Wall Modeled LES, and Hybrid RANS/LES simulations?
4	What **roadblocks in geometry preparation and mesh generation** for CFD prevent analysts from creating geometry/meshes suitable for high-lift aerodynamics simulations in a turn-key, rapid manner?
5	What was the **impact/effectiveness of the existing test data** collected for the CRM-HL configuration in understanding high-lift flow physics? If not effective, what is needed?
6	What are the **significant remaining technical areas** that require additional focus in future workshops?

KQ #1 – What CFD solution methodology(ies) currently provides the best/most-consistent approach to predicting (a) increments due to flap deflection, and (b) maximum lift?

- Test Case 3: Verification Study and Case 1b: Mesh convergence
- Test Case 1a: Flap deflection study
- Iterative convergence study
- Test Case 2a: $C_{L,max}$ study
- Velocity profile study
- Statistical Analysis

- Note: for KQ #1, we did not include effect of wind tunnel walls on the CFD – this was run by only a few participants

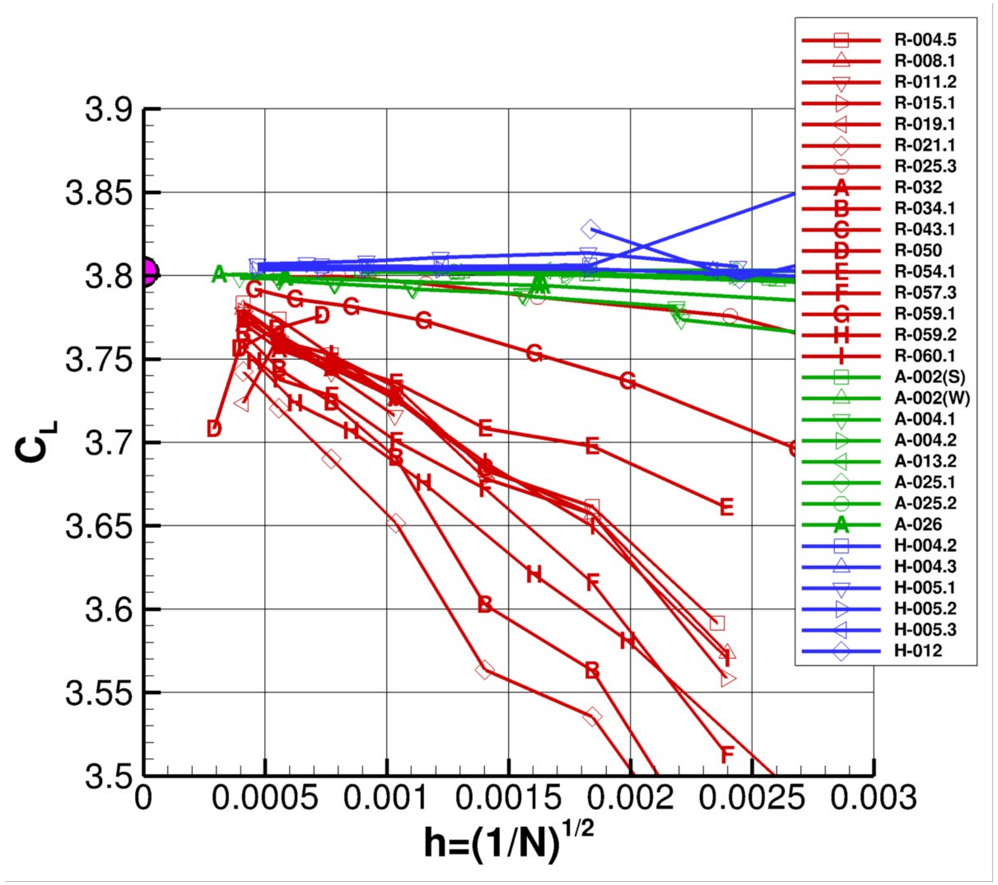
KQ#1, Test Cases 3 and 1b analysis

Test Case 3 – Verification Study

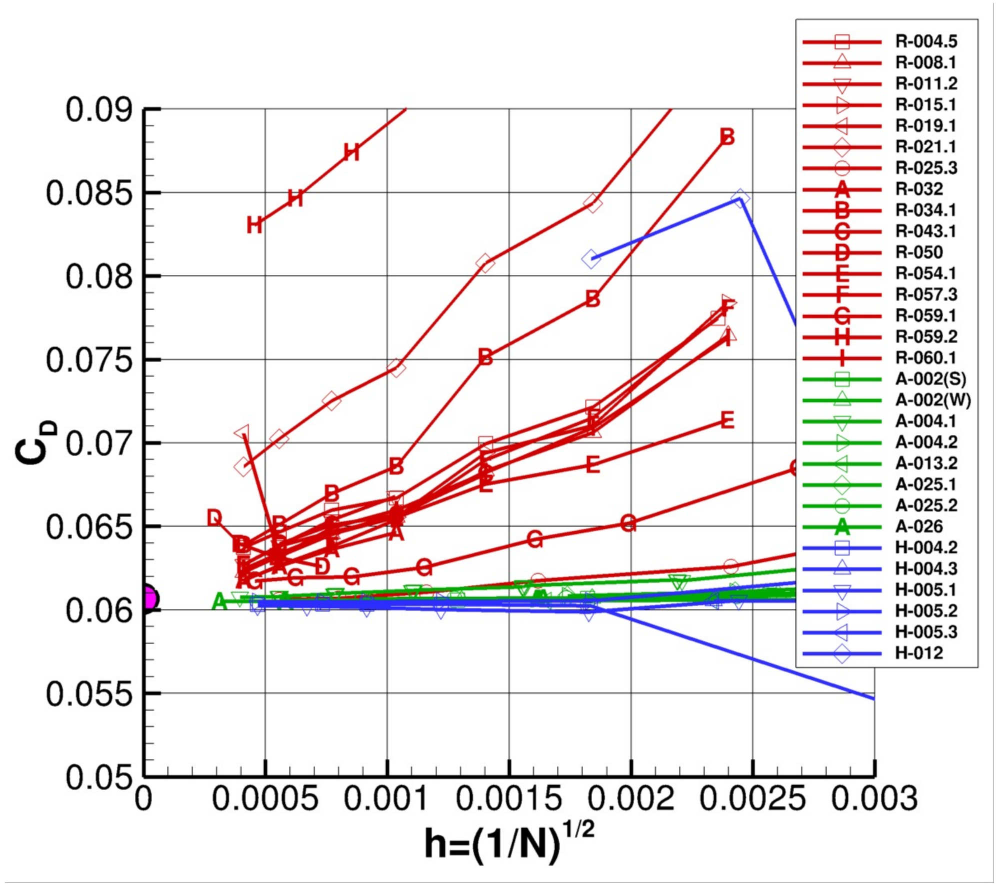
- Objective
  - Investigate consistency between RANS results using SA model
  - Test case is VERIF/2DMEA from NASA TMR website
- Background
  - This exercise helps find coding issues; if coded correctly, all results should go to the same answer as the mesh is refined
  - 2-D case puts “fine enough” grid within reach
- Data Comparisons
- Summary

Test Case 3 – SA Model Verification Study: Forces

Lift Coefficient



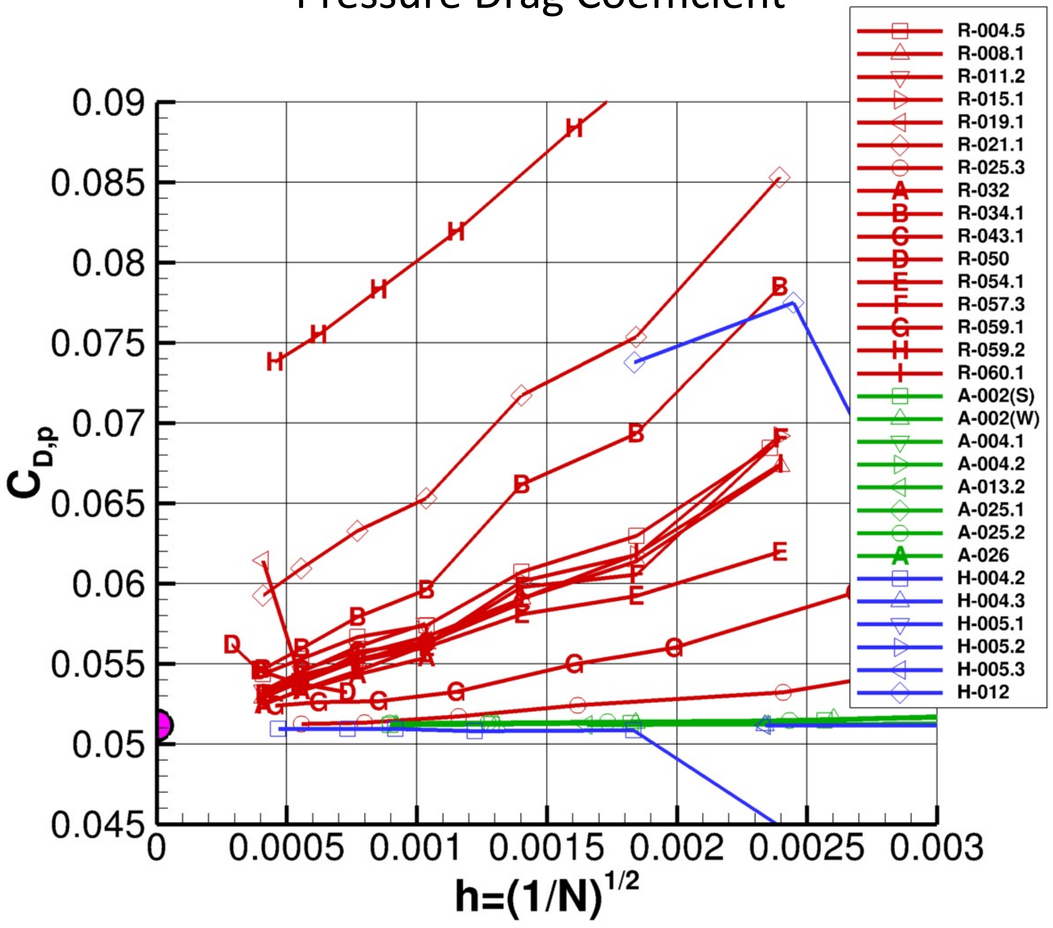
Drag Coefficient



Pink dot indicates approximate trend of grid-converged solutions
R-019.1, R-050, R-059.2, and H-012 are conspicuously off from all the others

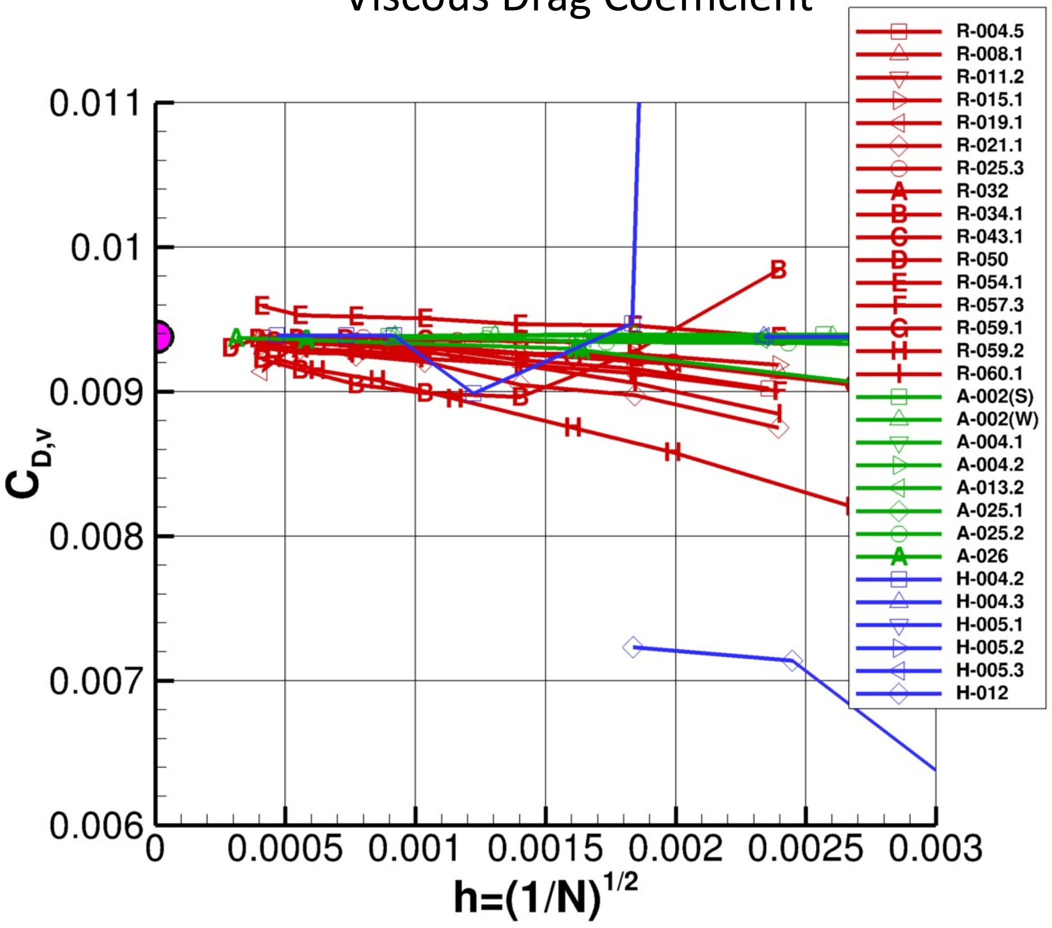
Test Case 3 – SA Model Verification Study: Forces

Pressure Drag Coefficient



Similar conclusions here

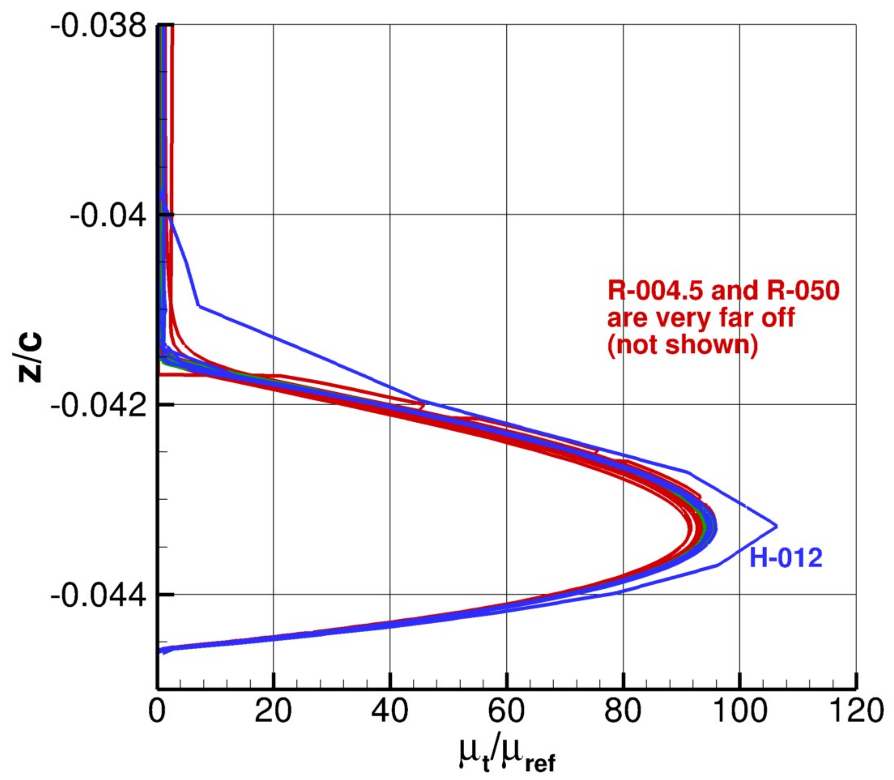
Viscous Drag Coefficient

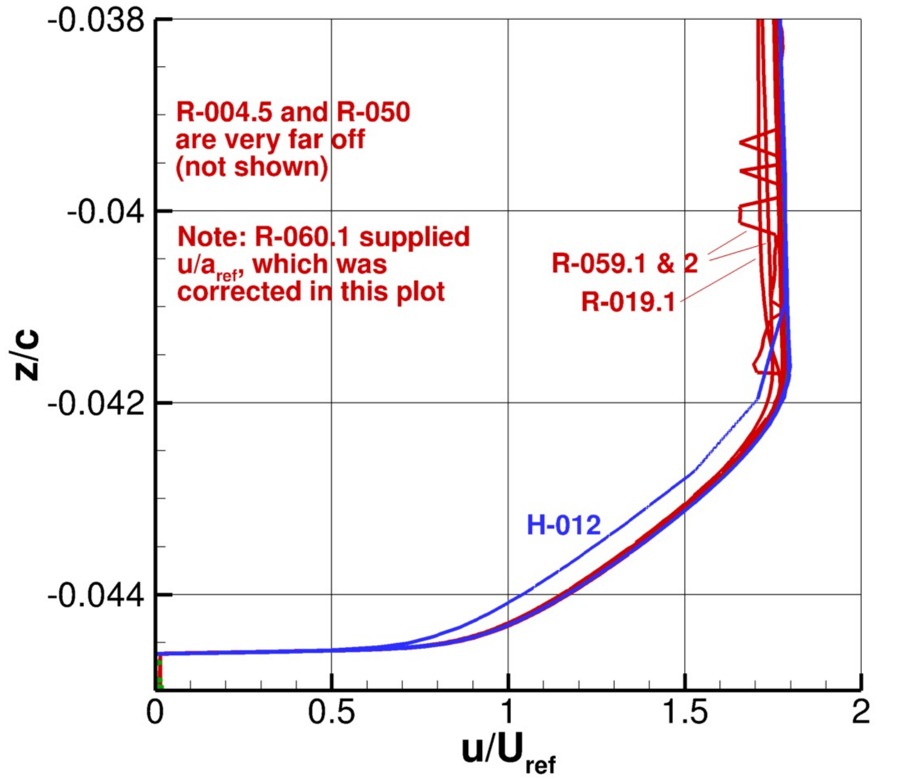


For R-054.1, $C_{D,v}$ is trending away (slightly) on the finest grid

Test Case 3 – SA Model Verification Study: Profiles

Over Slat at x/c=-0.03





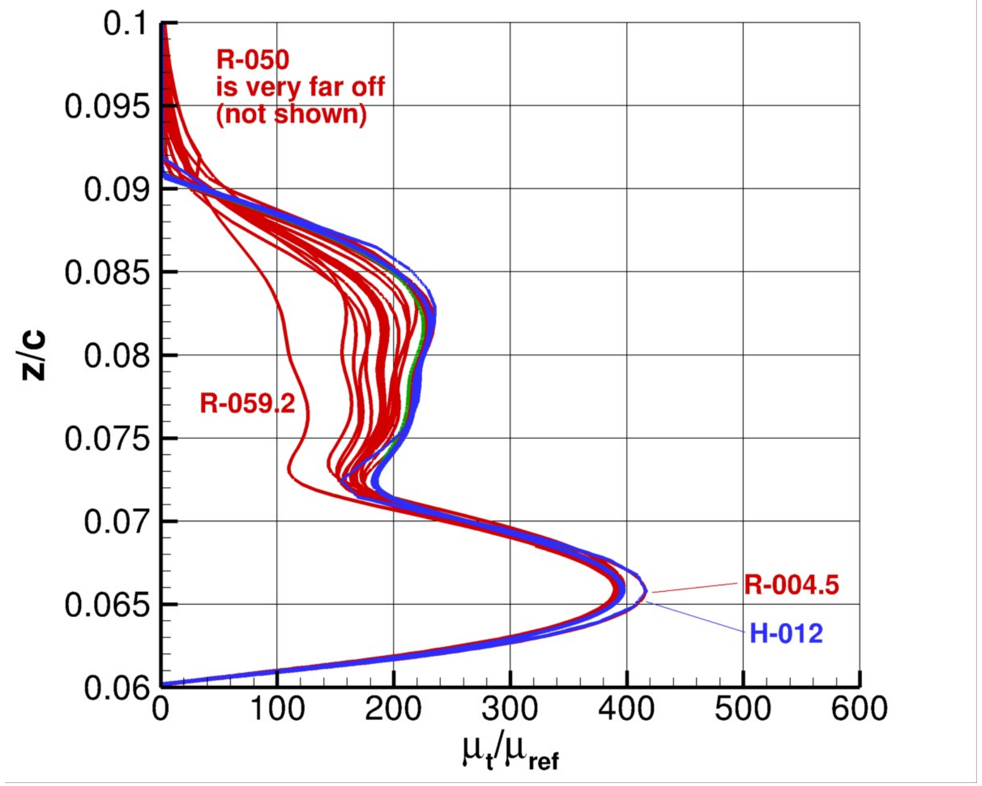
Velocity and eddy viscosity profiles of a few submission results lie somewhat "away from the pack" in the boundary layer

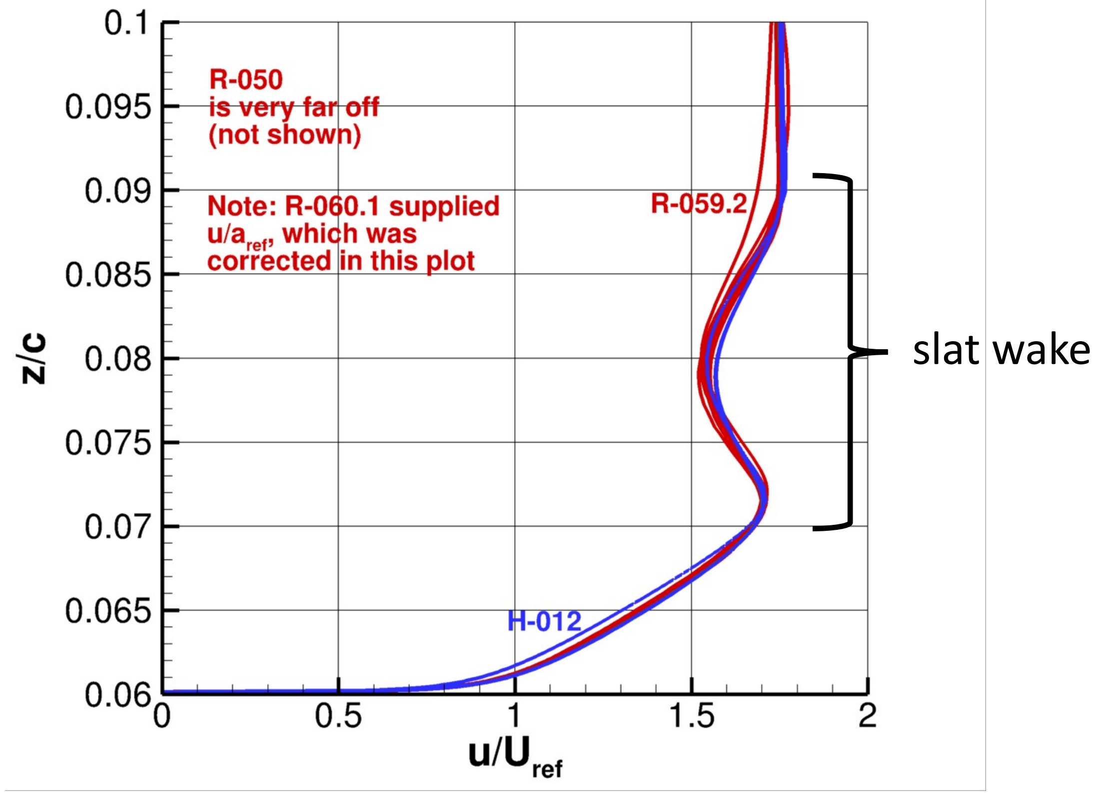
Most ADAPT and HO results agree nearly perfectly

- Exception: H-012 has large differences

Test Case 3 – SA Model Verification Study: Profiles

Over Main at x/c=0.40





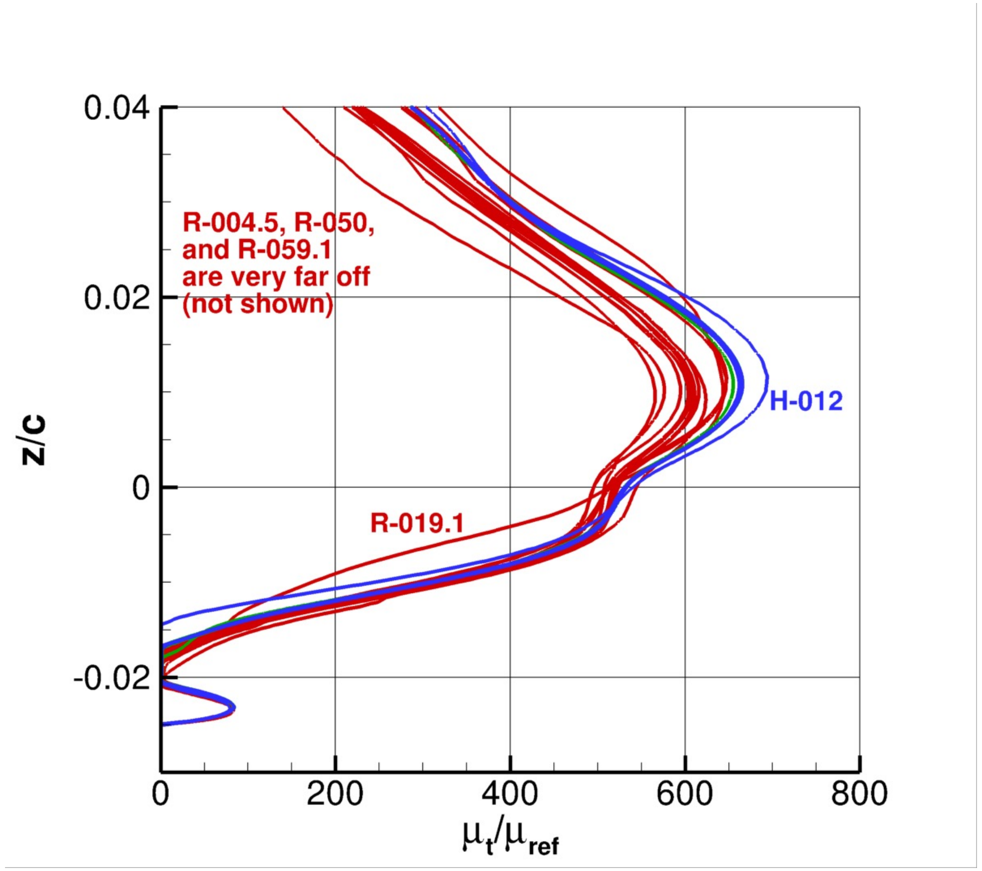
The slat wake region shows much variation among all RANS results

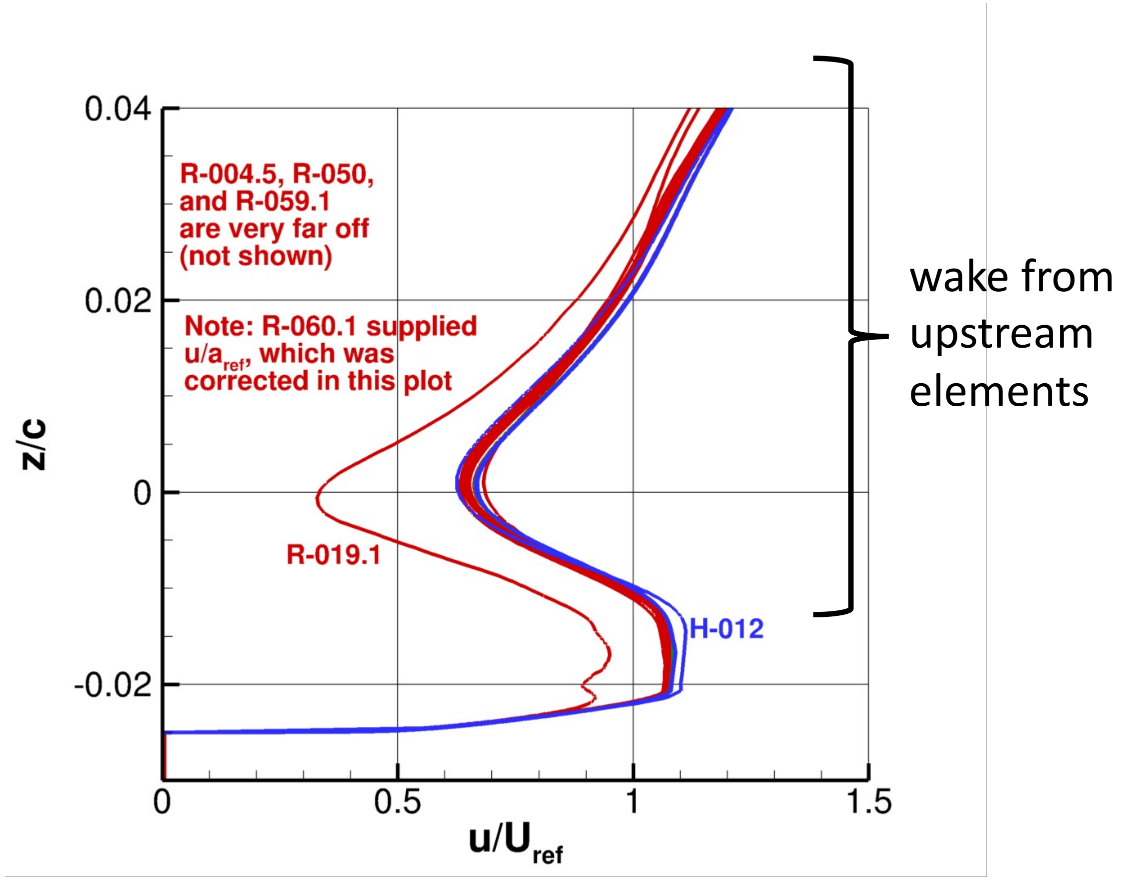
Most ADAPT and HO results agree nearly perfectly everywhere

- Exceptions: A-026 has very slight differences and H-012 has large differences

Test Case 3 – SA Model Verification Study: Profiles

Over Flap at x/c=0.95





The wake region again shows much variation among all RANS results

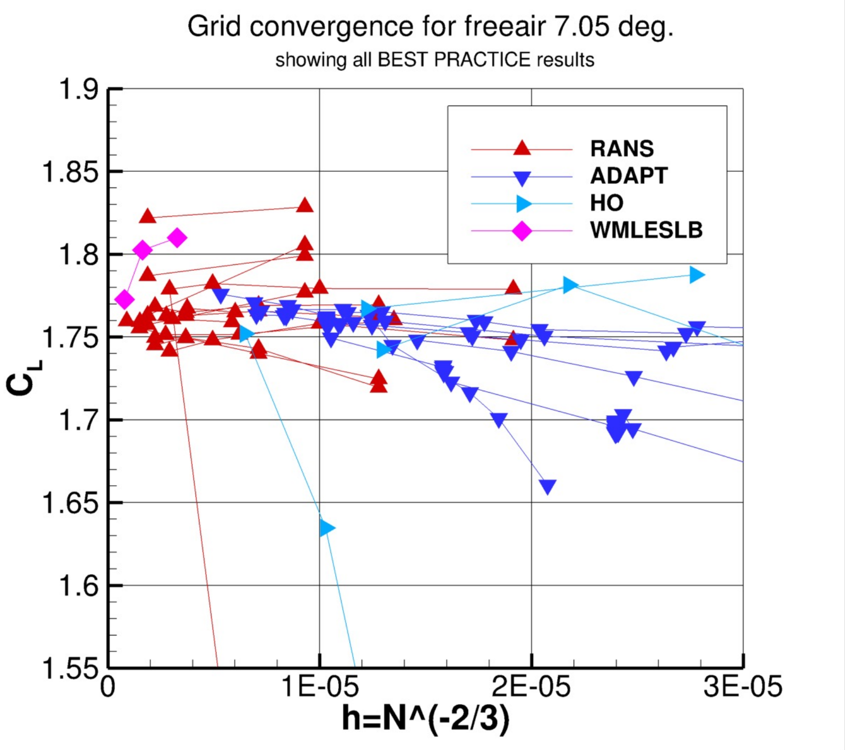
Most ADAPT and HO results agree nearly perfectly everywhere

- Exceptions: A-026 has very slight differences and H-012 has large differences

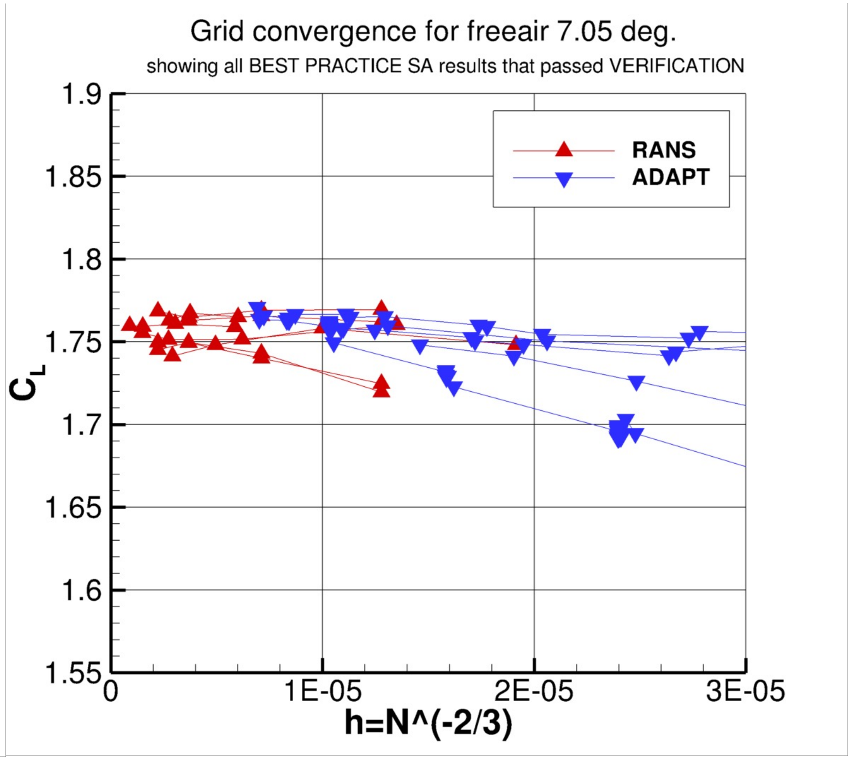
Test Case 1b (accounting for verification results)

- Verified*:
  - R-008.1, R-011.2, R-015.1, R-021.1, R-025.3, R-032, R-034.1, R-043.1, R-057.3, R-060.1
  - A-002, A-004.1, A-004.2, A-013.2, A-025.1, A-025.2, A-026
  - H-004.2, H-004.3, H-005.1, H-005.2, H-005.3
- Very close or some mistakes in entry (not sure):
  - R-004.5, R-054.1, R-059.1
- Not verified:
  - R-019.1, R-050, R-059.2 (reduced order)
  - H-012
- Case 3 data not submitted:
  - R-009, R-028, R-037
  - A-031
  - H-013

All Best Practice Results for Case 1b



All Best Practice Results for Case 1b that passed SA verification test



* By the standards examined so far

Note: WMLESLB does not have a verification test

Test Case 3 and 1b – Summary

- Most ADAPT and HO results agreed nearly perfectly for case 3
  - RANS results showed spread in eddy viscosity, especially in the wake regions
    - Conclusion: current fixed grids not fine enough to capture wake characteristics when using typical RANS numerics (often 1st order for turbulence advection)
- 22 out of 29 case 3 SA submissions were crudely "verified" (75%)
  - Dramatic improvement from HLPW-3, when only 30% were verified
  - 5 RANS/ADAPT/HO participants did not submit case 3 data
- When looking at verified SA results for Case 1b (AoA=7.05 deg.):
  - C_L results were fairly tight on finest grids (within about $\Delta C_L = 0.04$)
  - Much tighter than overall scatter range of 0.15 from HLPW-3
  - Also tighter than RANS scatter range (for all turbulence models) from this workshop of 0.09
  - ADAPT results were significantly tighter than fixed-grid RANS results (using less gridpoints)

KQ#1, Test Case 1a analysis

Test Case 1a – Flap Deflection Study

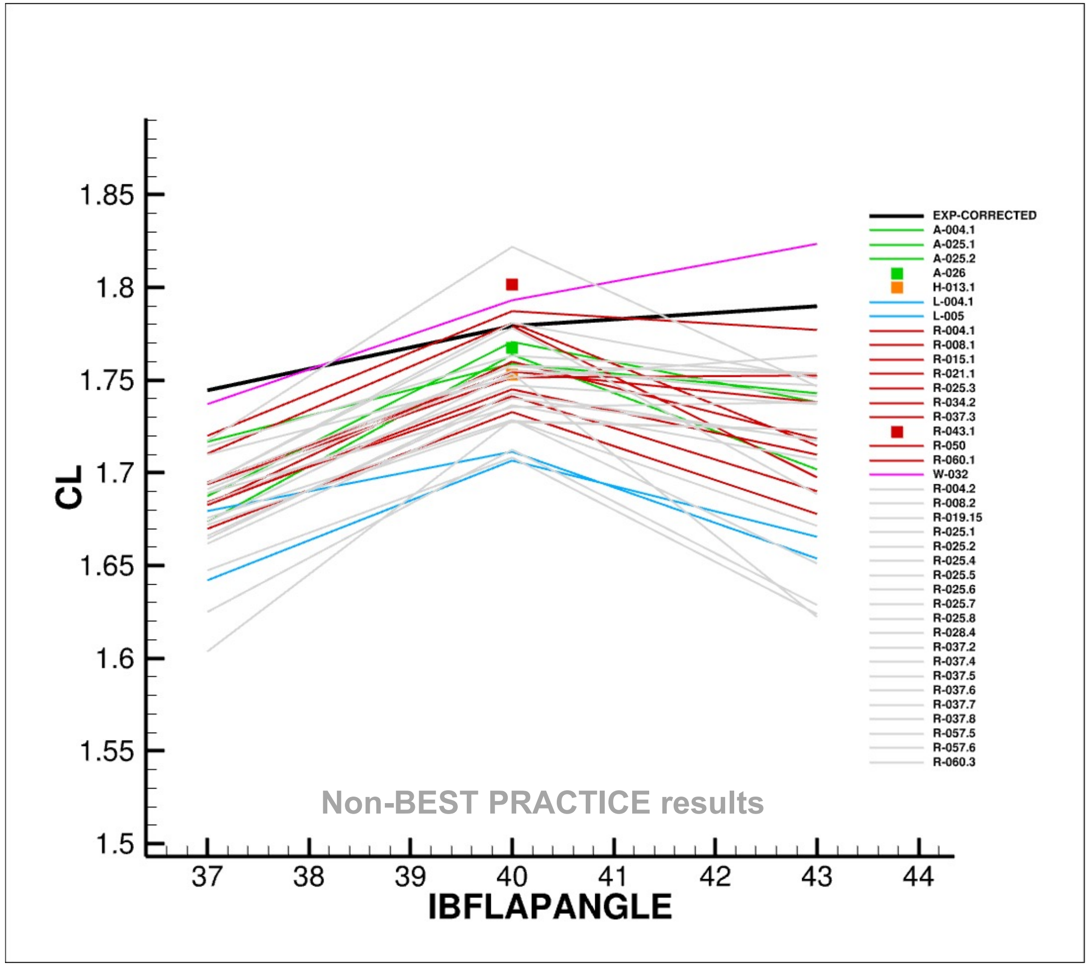
- Objective
  - Determine ability of CFD to predict force and moment increments for three flap deflections at a nominal angle-of-attack
- Background
  - Test case was blind in Summer Progress Meeting
  - Focused on BEST PRACTICE results, although looked at all available
  - Looking for both consistency in the CFD, and accuracy in predicting trends
  - Considered all available participant data to explain trends
- Data Comparisons
- Summary

Test Case 1a – Flap Deflection Study

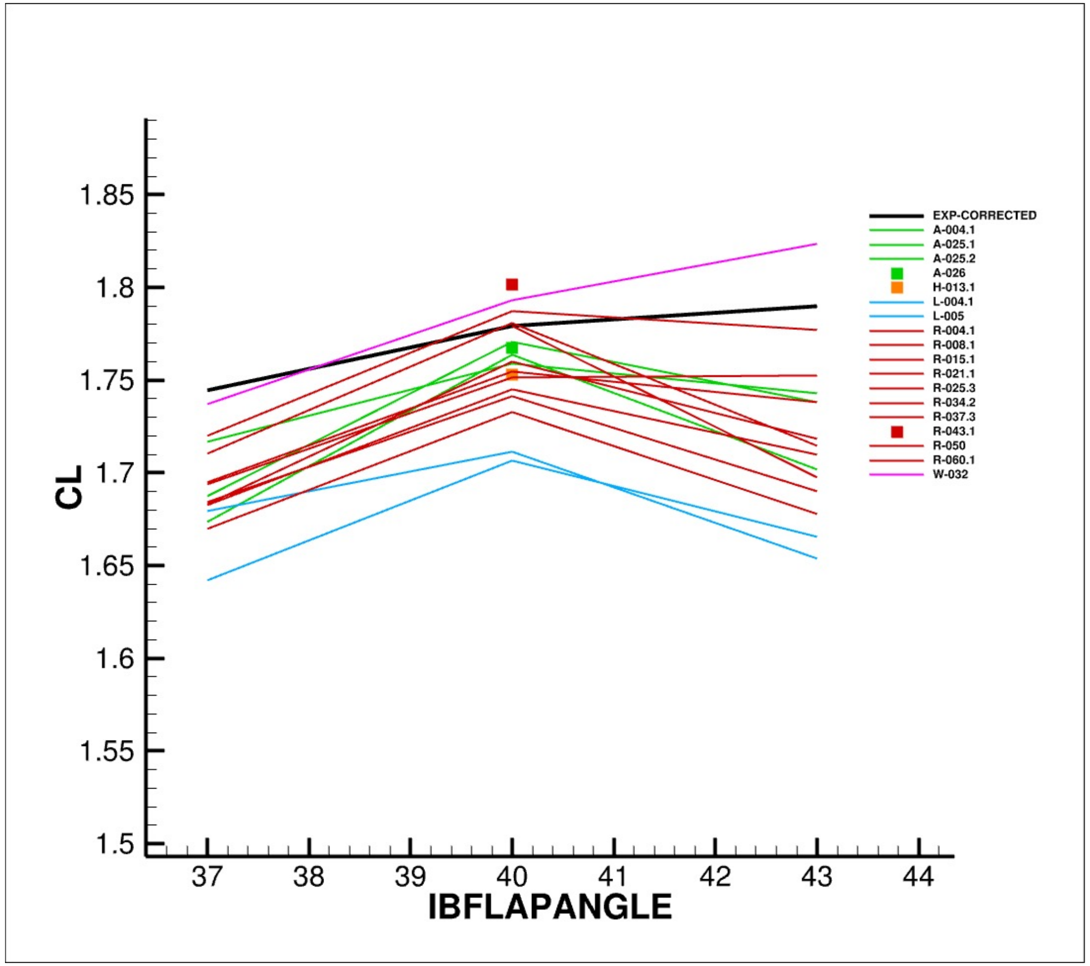
Mach Number	0.2
Angle of Attack	7.01° (wall corrected)
Reynolds Number based on MAC	5.49 million
Reference Static Temperature	521 °R
Reference Static Pressure	24.67 psi
Mean Aerodynamic Chord (MAC)	275.8 inches
Moment Reference Center (MRC)	x = 1325.9 inches, y = 0.0 inches, z = 177.95 inches
Flap Deflection	3 different geometries: • 40°/37° inboard/outboard (nominal) • 37°/34° inboard/outboard • 43°/40° inboard/outboard
Important Details:	• Geometry is given in full-scale inches. • For RANS, run simulations fully turbulent. • All simulations are “free air”; no wind tunnel walls or model support systems. (The 7.01° angle in free air corresponds with 6° incidence when tunnel walls are included.)
Data Delivery	Forces/moments, surface pressures, surface streamlines

Test Case 1a – Flap Deflection Study

Lift Coefficient – All Datasets (40)

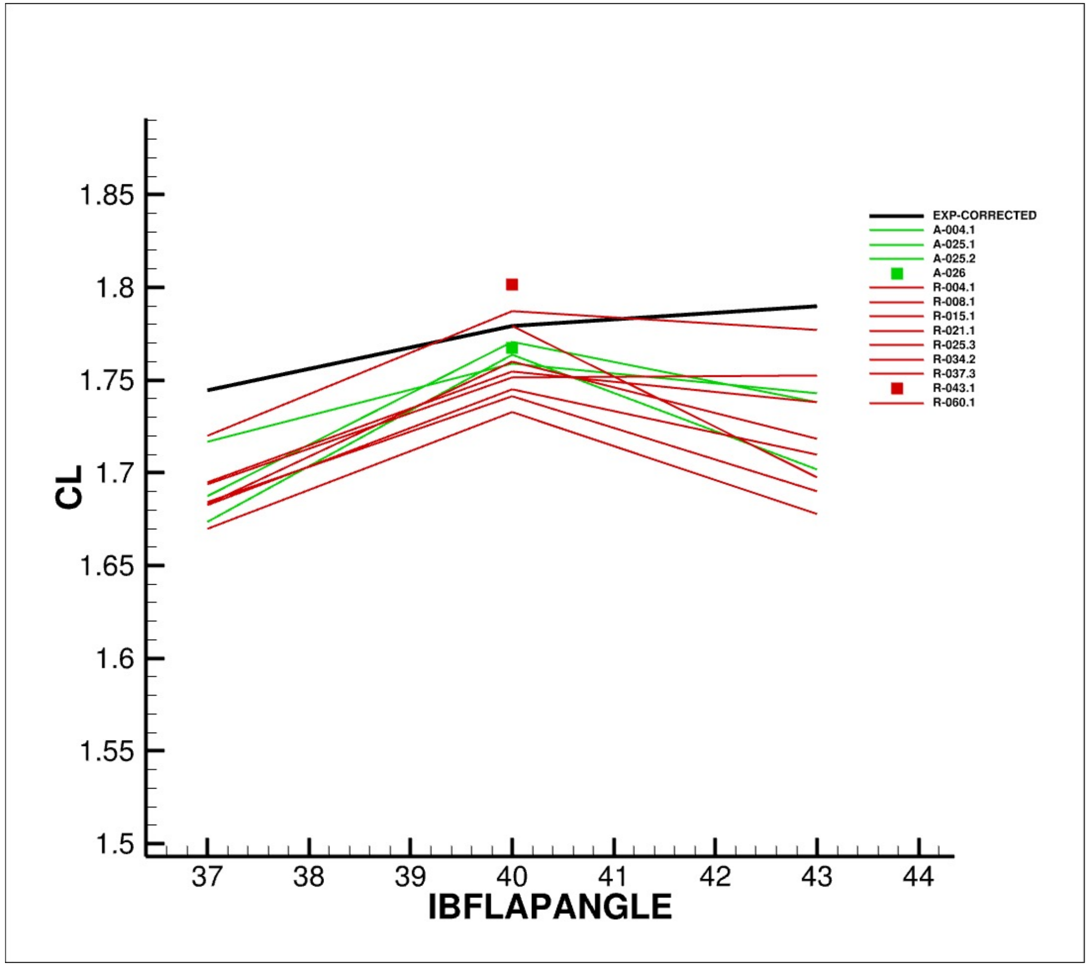


Lift Coefficient – BEST PRACTICE (18)

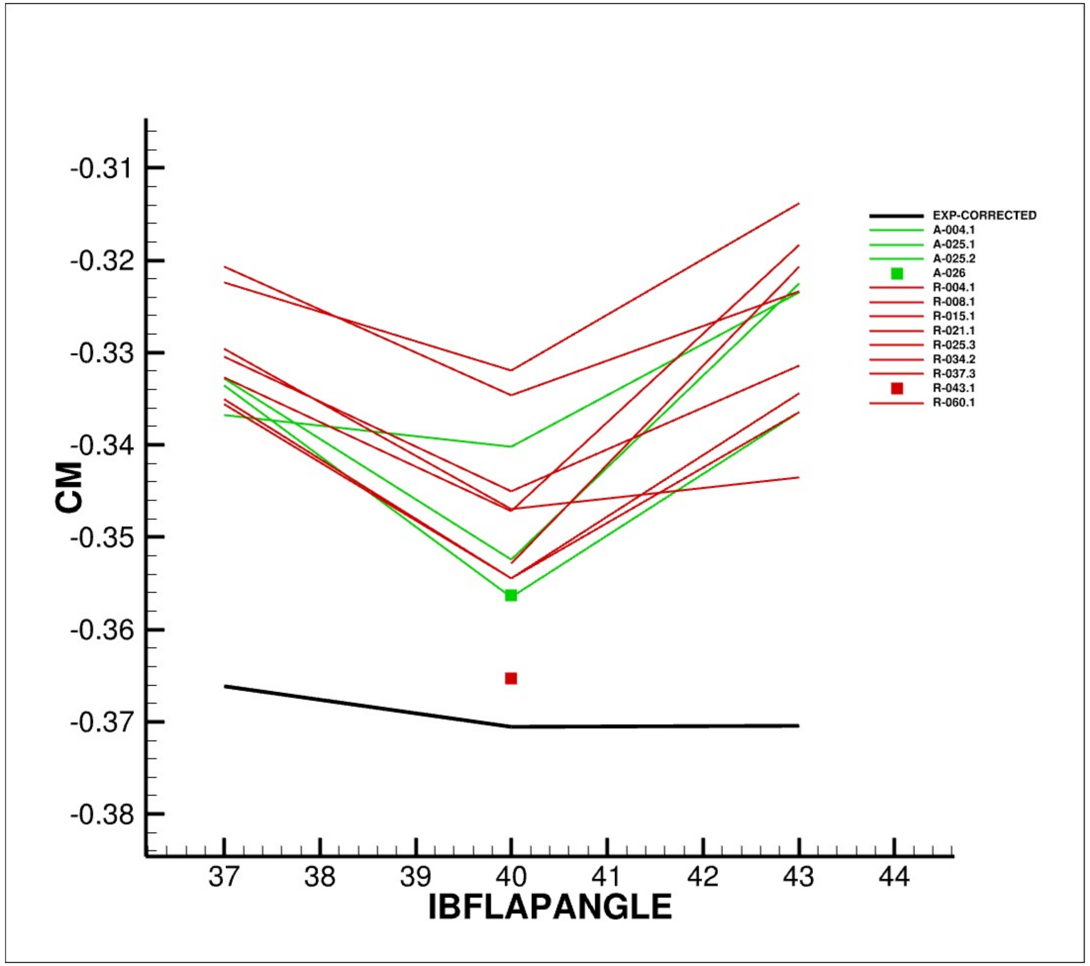


Test Case 1a – Flap Deflection Study

Lift Coefficient – BP + Verified (13)

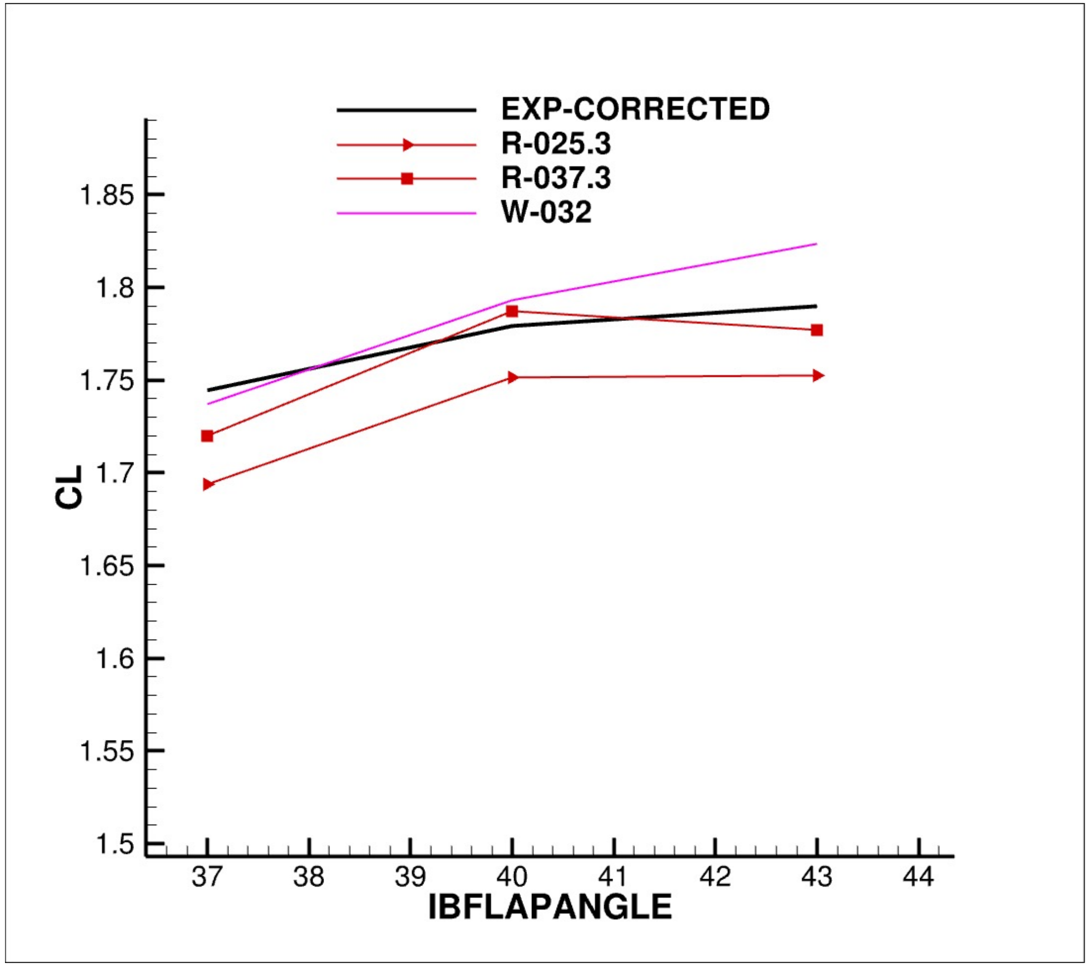


Pitching Moment Coefficient – BP + Verified (13)

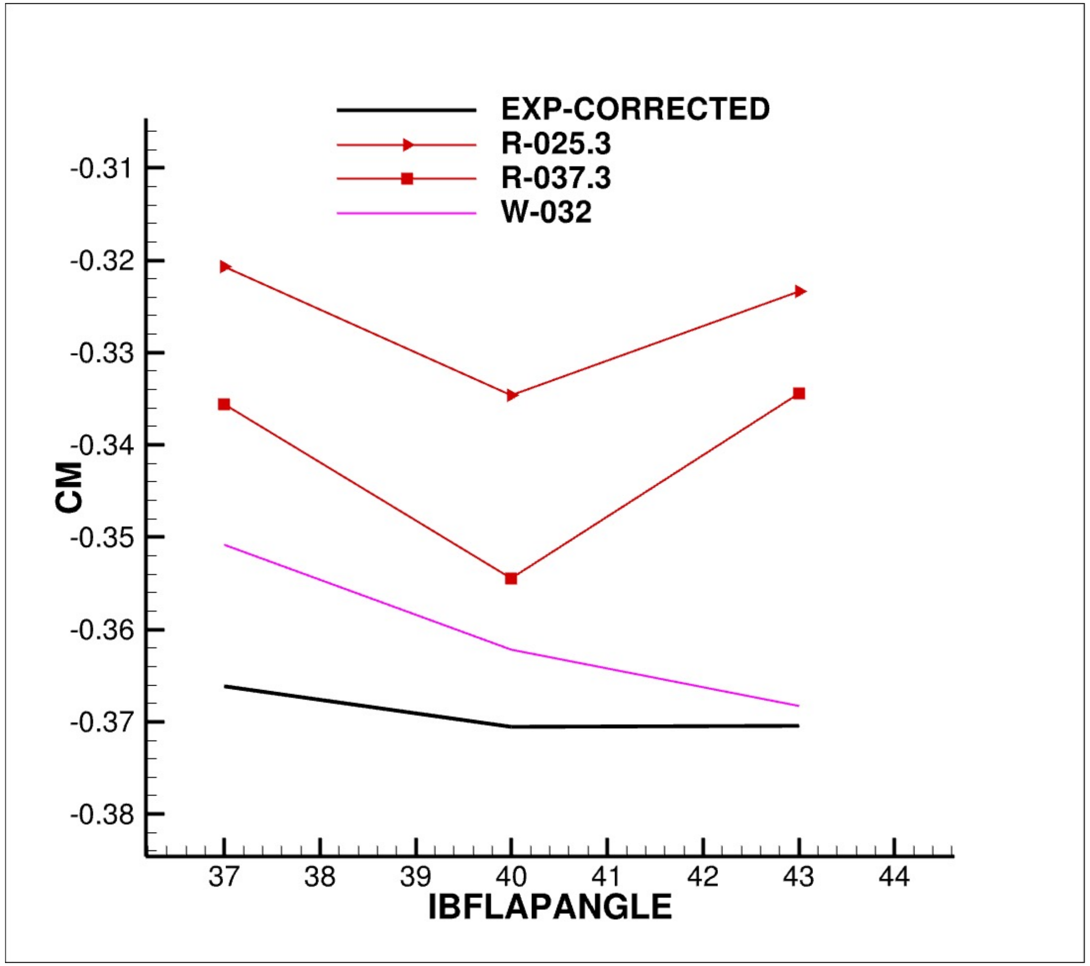


Test Case 1a – Flap Deflection Study

Lift Coefficient – Selected (3)

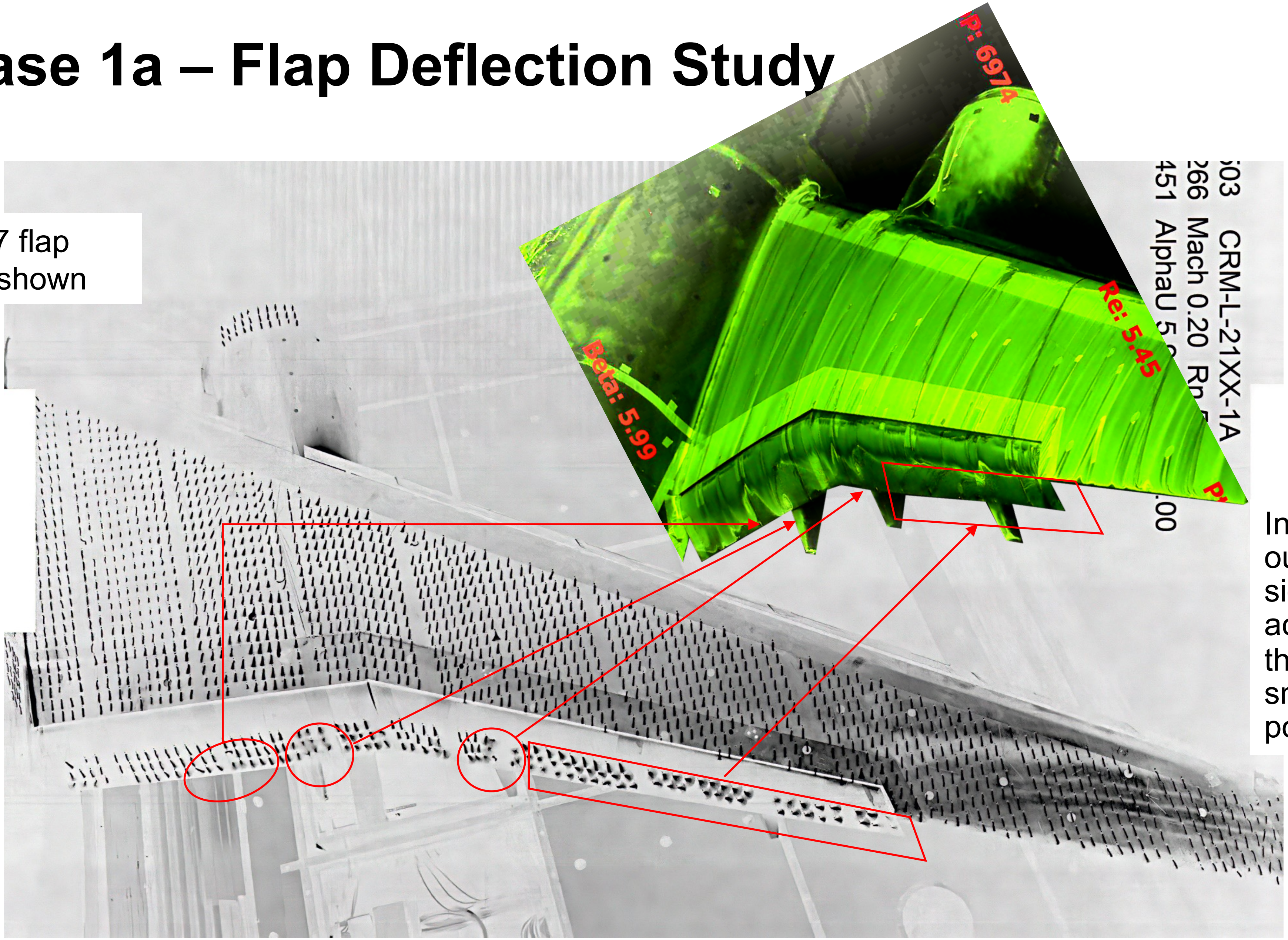


Pitching Moment Coefficient – Selected (3)



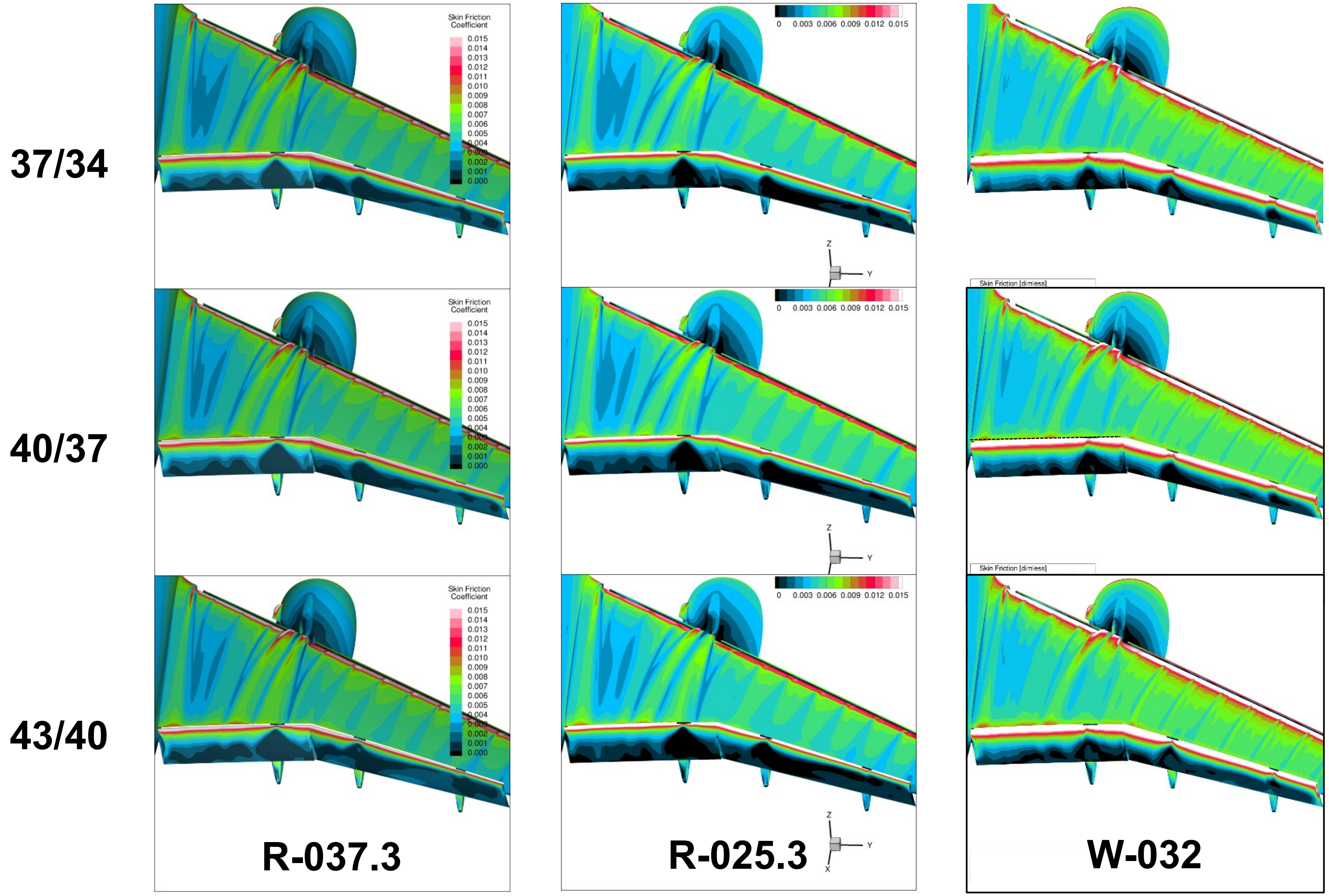
Test Case 1a – Flap Deflection Study

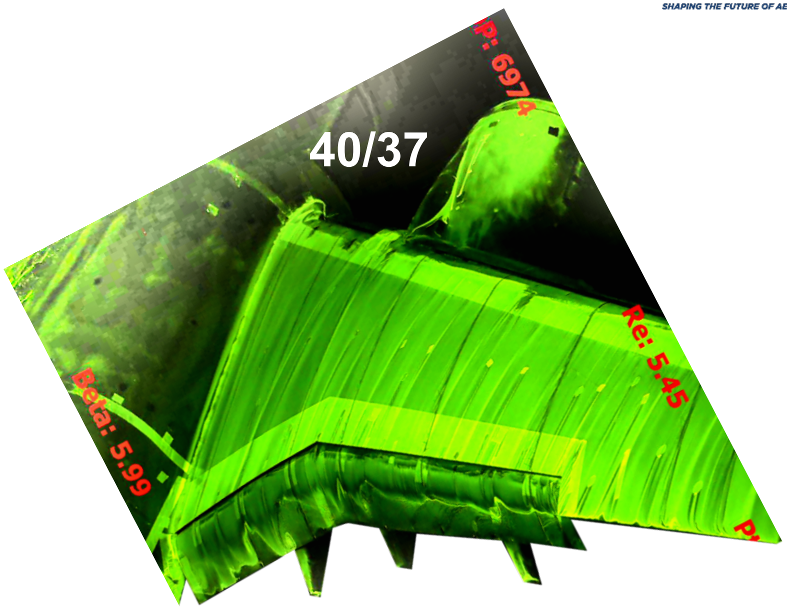
Nominal 40/37 flap configuration shown



In the wind tunnel, the outboard flap had significant separation across the span, and the inboard flap had smaller, more isolated pockets of separation

Test Case 1a – Flap Deflection Study





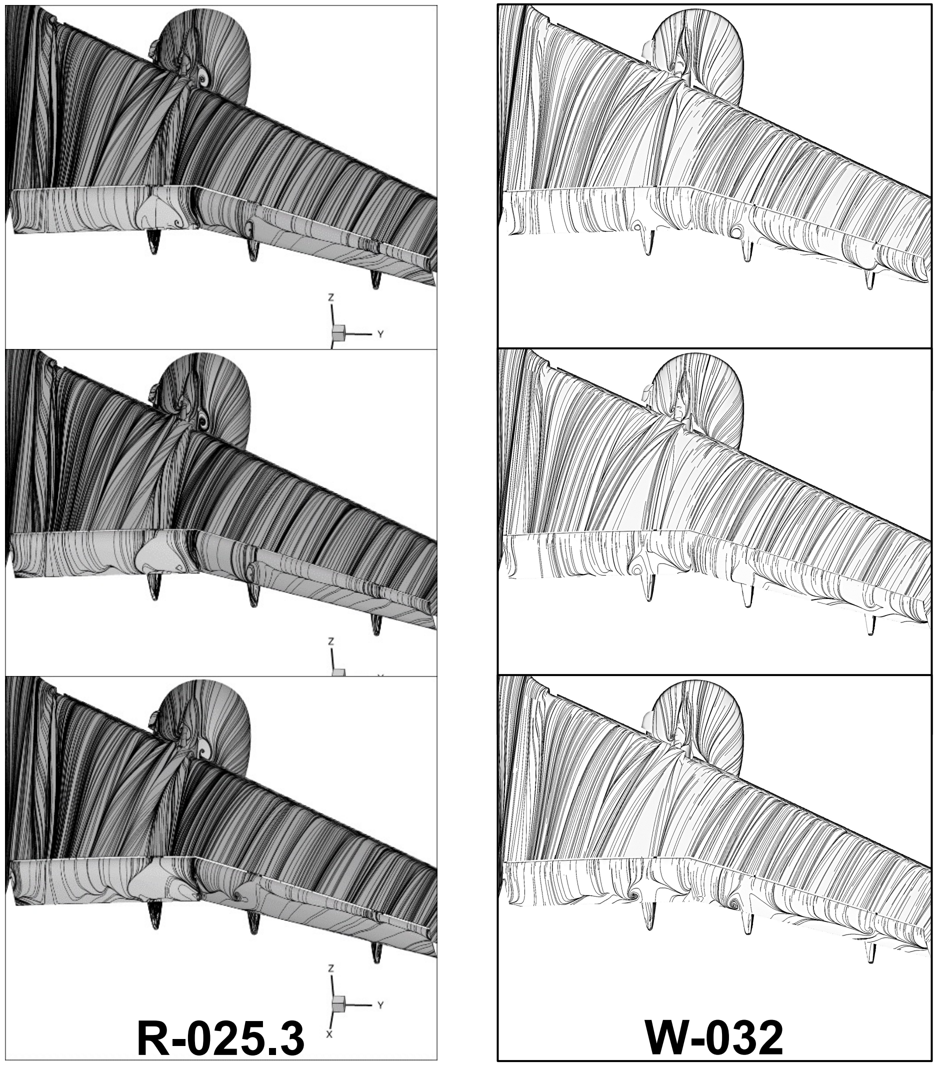
- R-037.3 and R-025.3 show qualitatively similar results using same grid but different solver
- W-032 shows less separation of wing upper surface, and generally higher leading edge (LE) suction peaks on the wing and flap elements
- Flap separation looks qualitatively similar for all CFD simulations across all flap detents

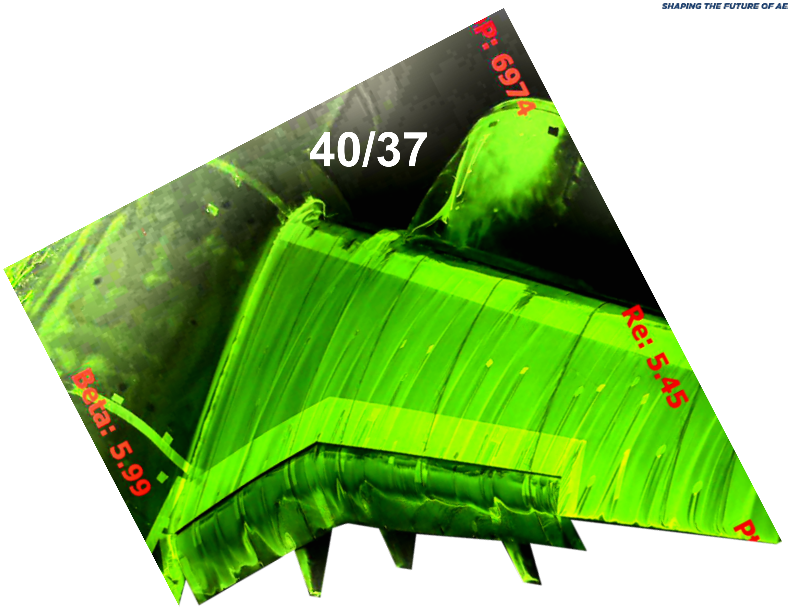
Test Case 1a – Flap Deflection Study

37/34

40/37

43/40

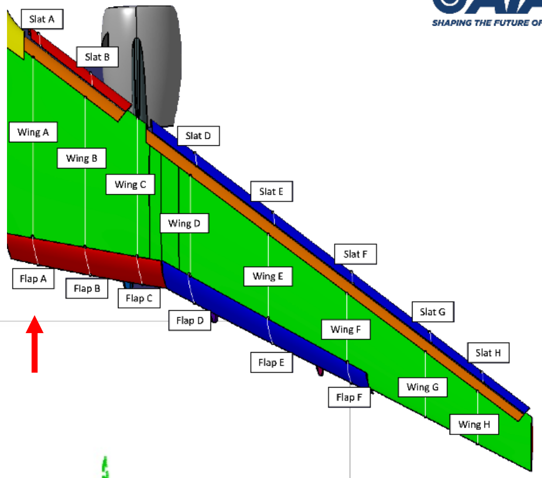


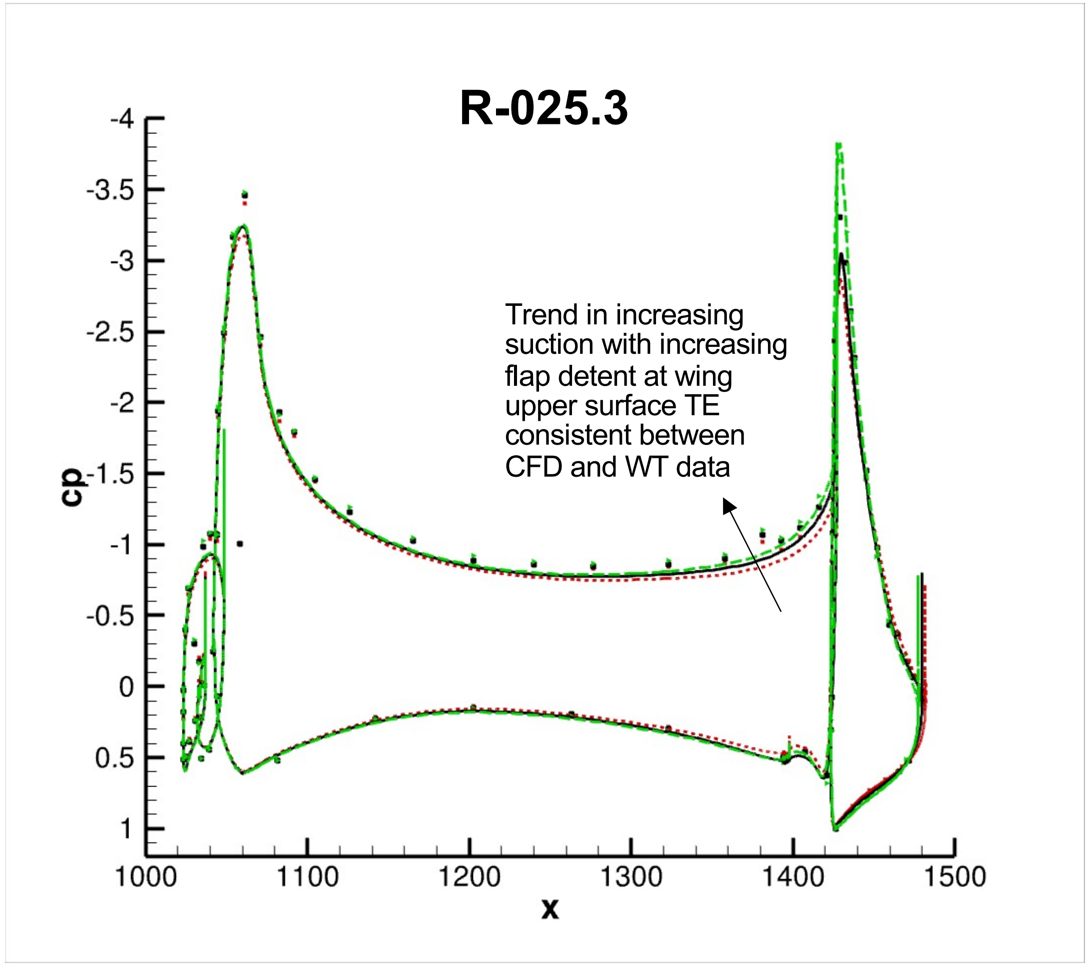


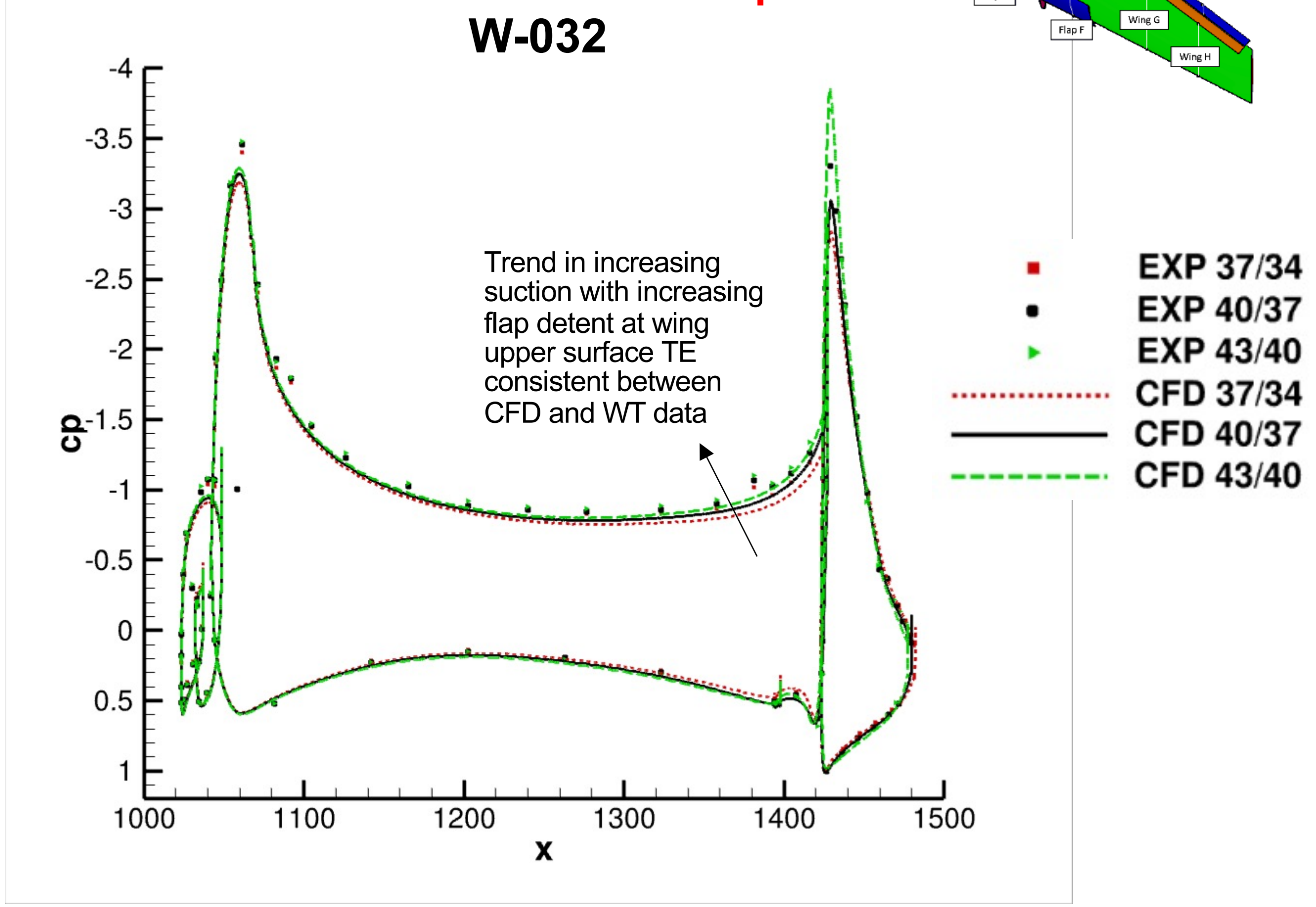
- R-025.3 simulation shows larger flap separation relative to W-032 simulation, particularly at outboard end of IB flap and along span of OB flap

Test Case 1a – Flap Deflection Study

Comparison of Surface Pressures - ROW A

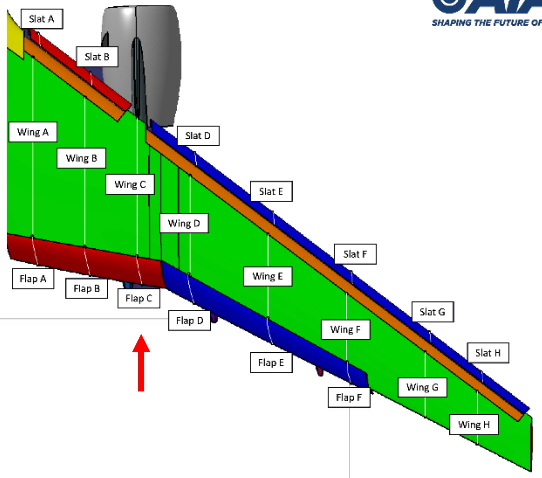


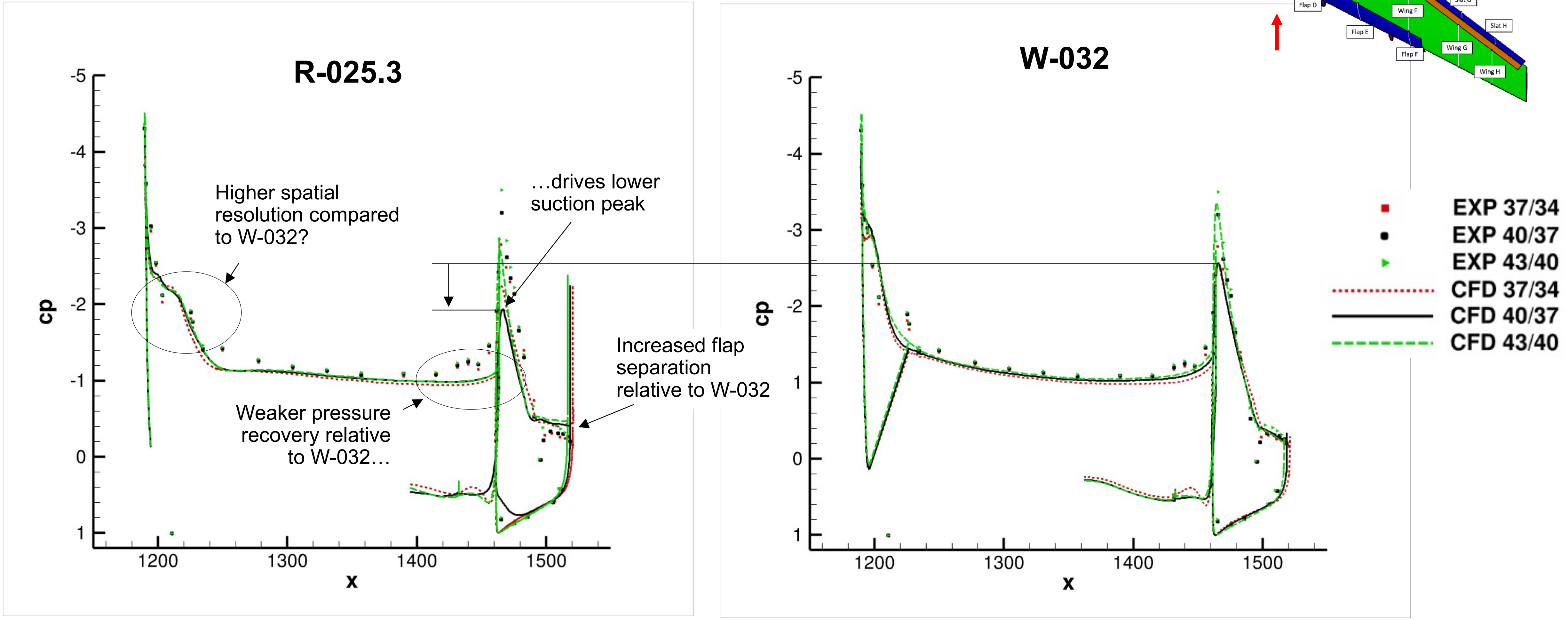




Test Case 1a – Flap Deflection Study

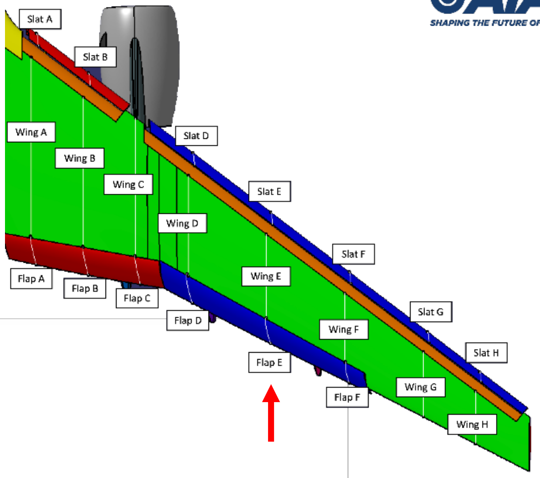
Comparison of Surface Pressures - ROW C

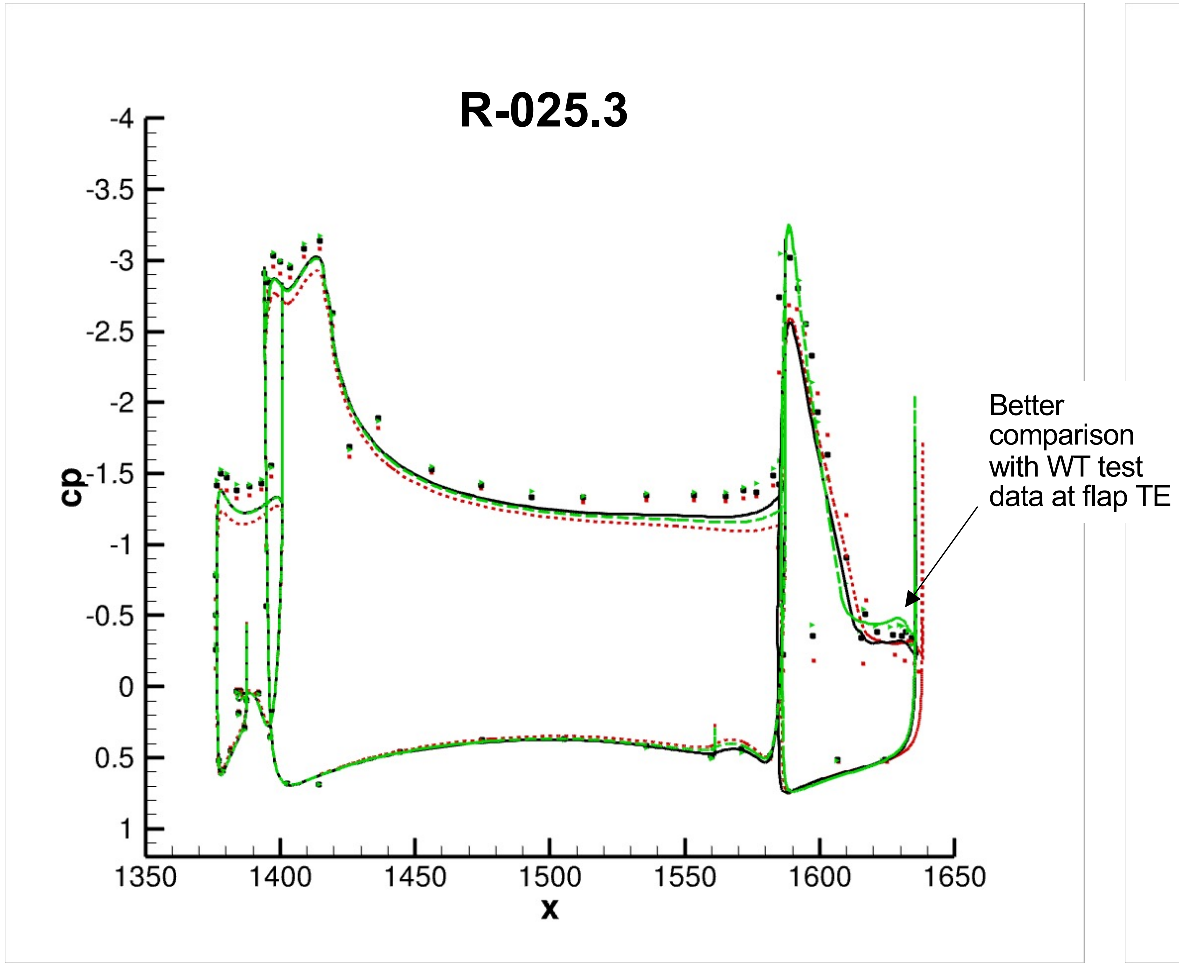


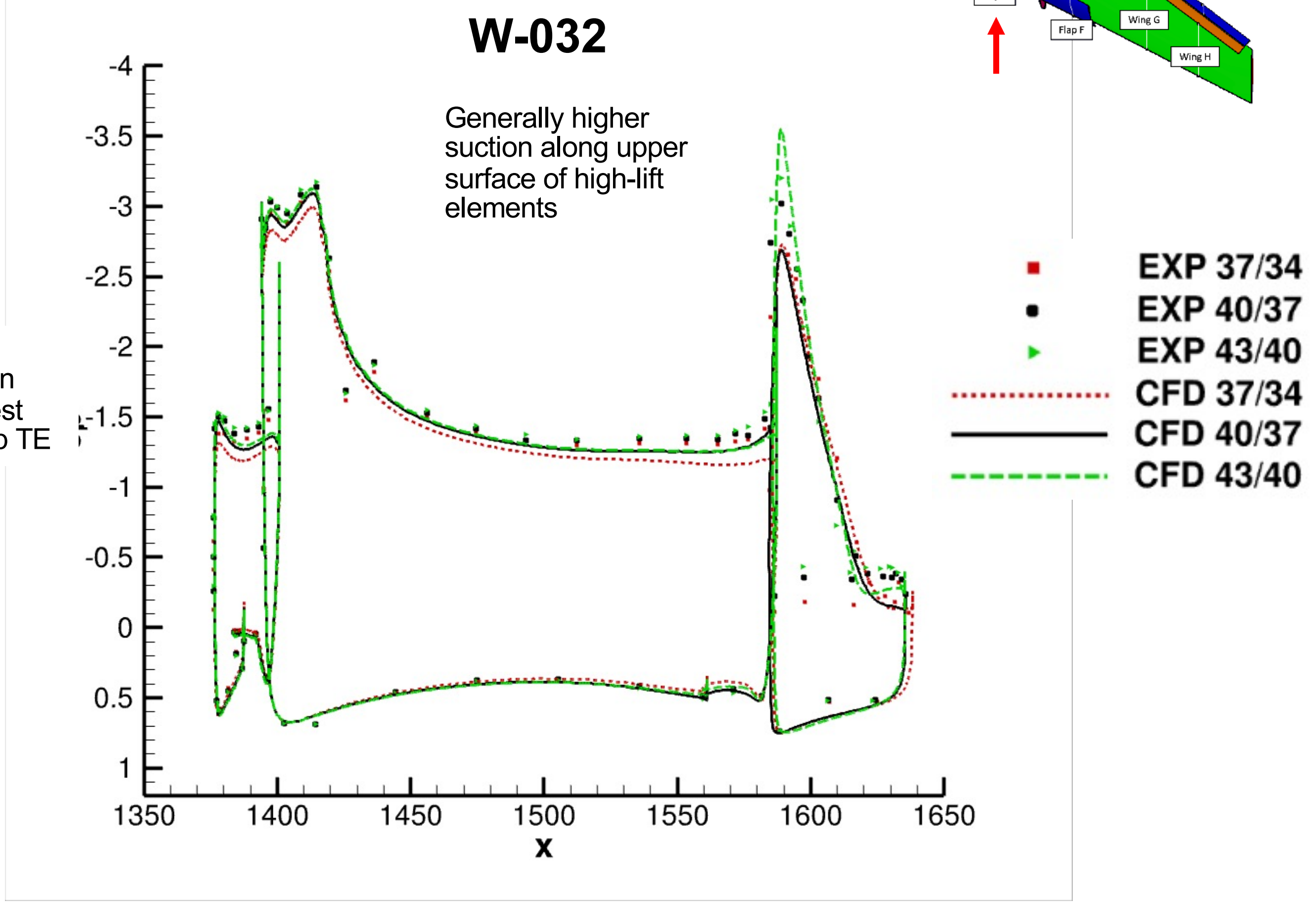


Test Case 1a – Flap Deflection Study

Comparison of Surface Pressures - ROW E





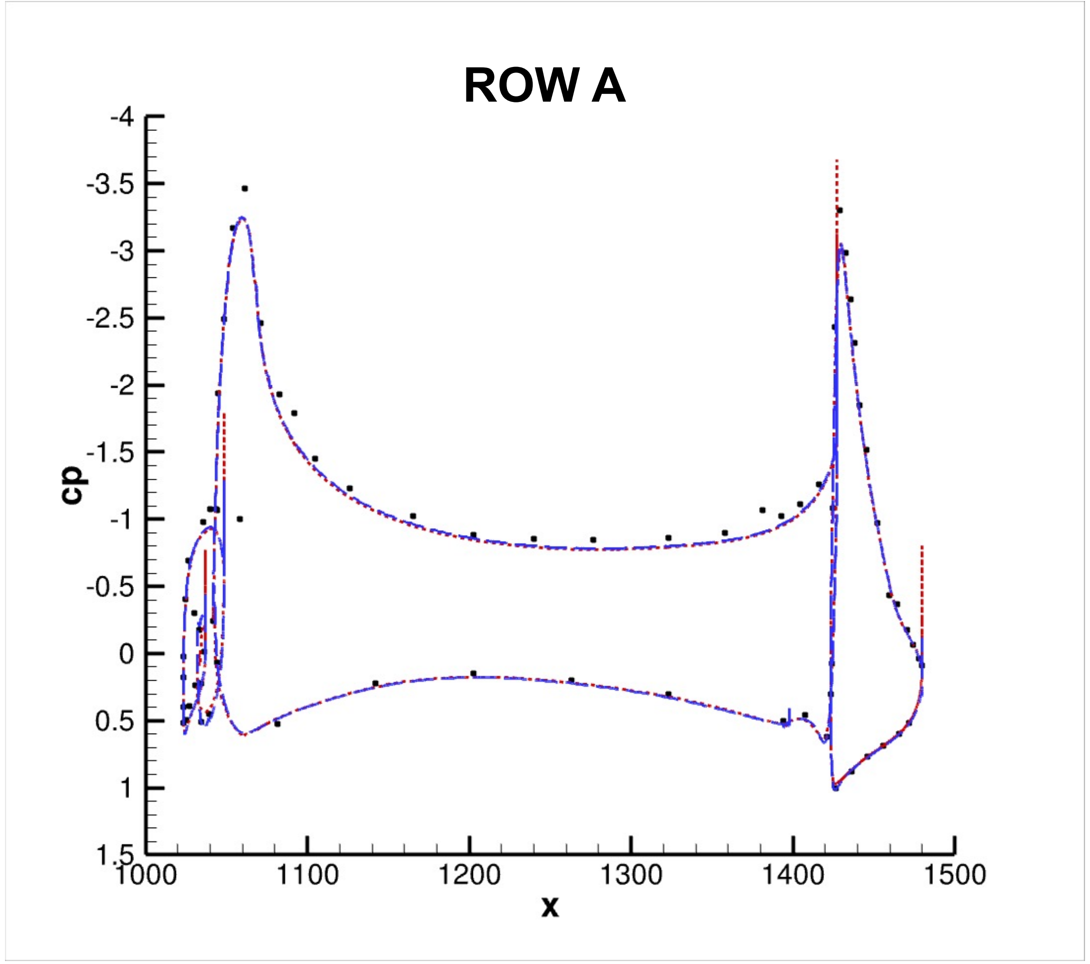


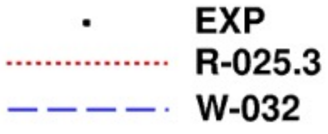
Test Case 1a – Flap Deflection Study

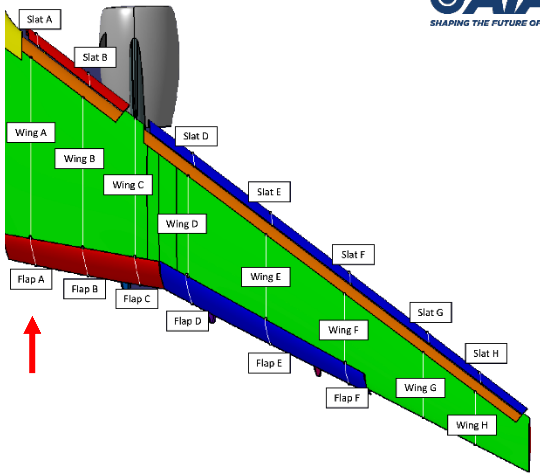
Comparison of Surface Pressures - Flap 40/37

No discernible difference in pressure distribution at this spanwise location

Both simulations model flow reasonably well, except for LE pressure peaks





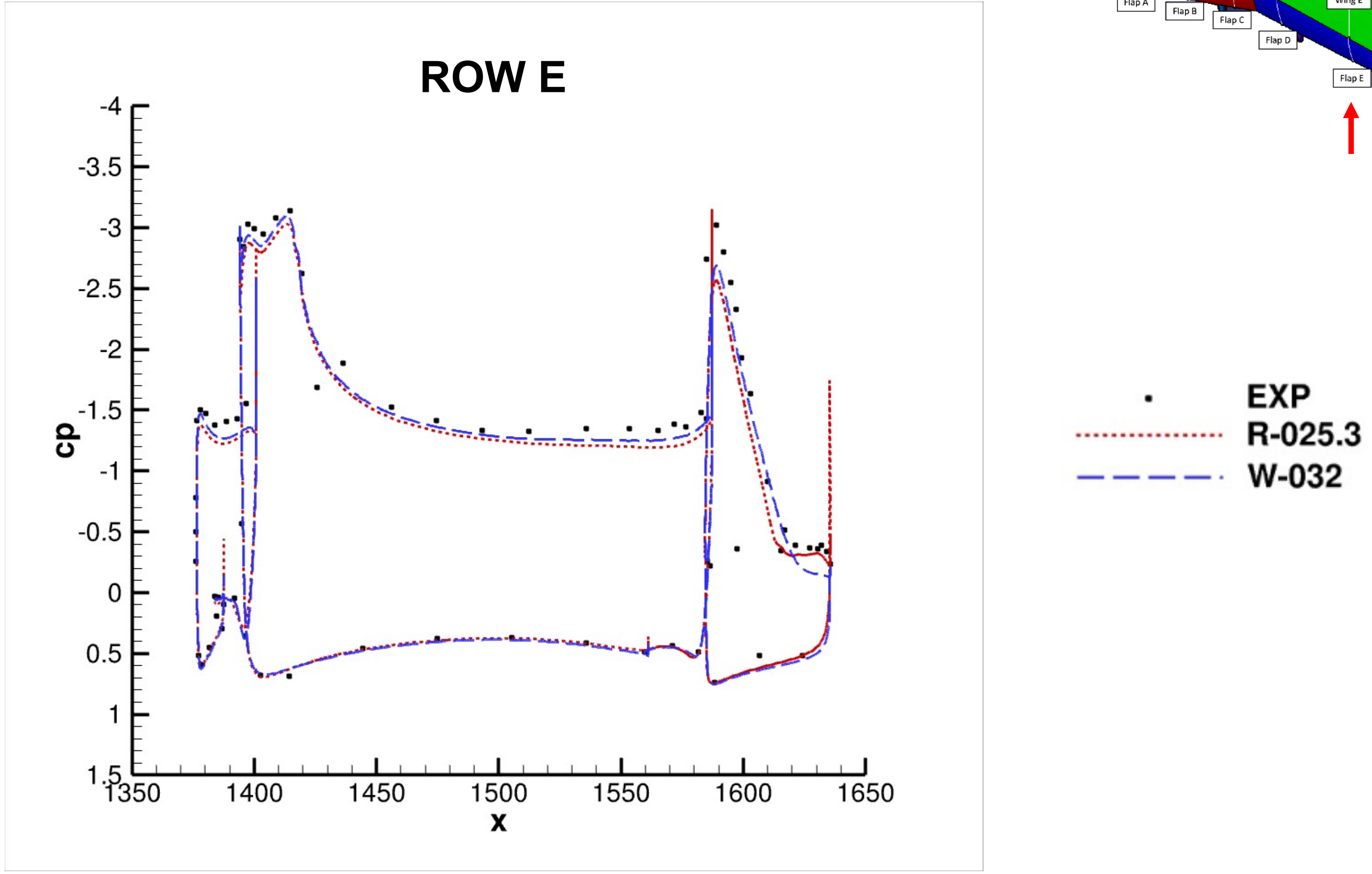


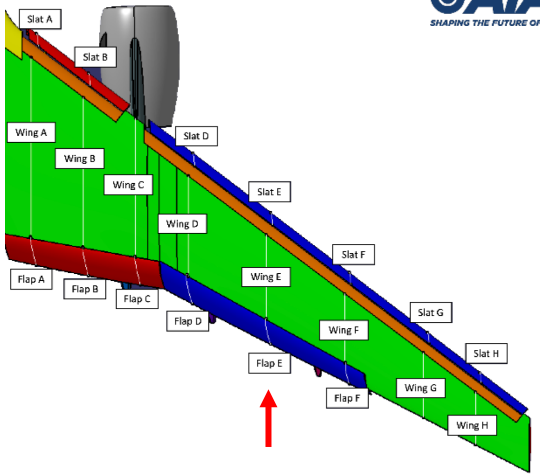
Test Case 1a – Flap Deflection Study

Comparison of Surface Pressures - Flap 40/37

W-032 shows slightly better agreement with WT test data for all elements

R-025.3 shows better agreement with WT test data at flap TE

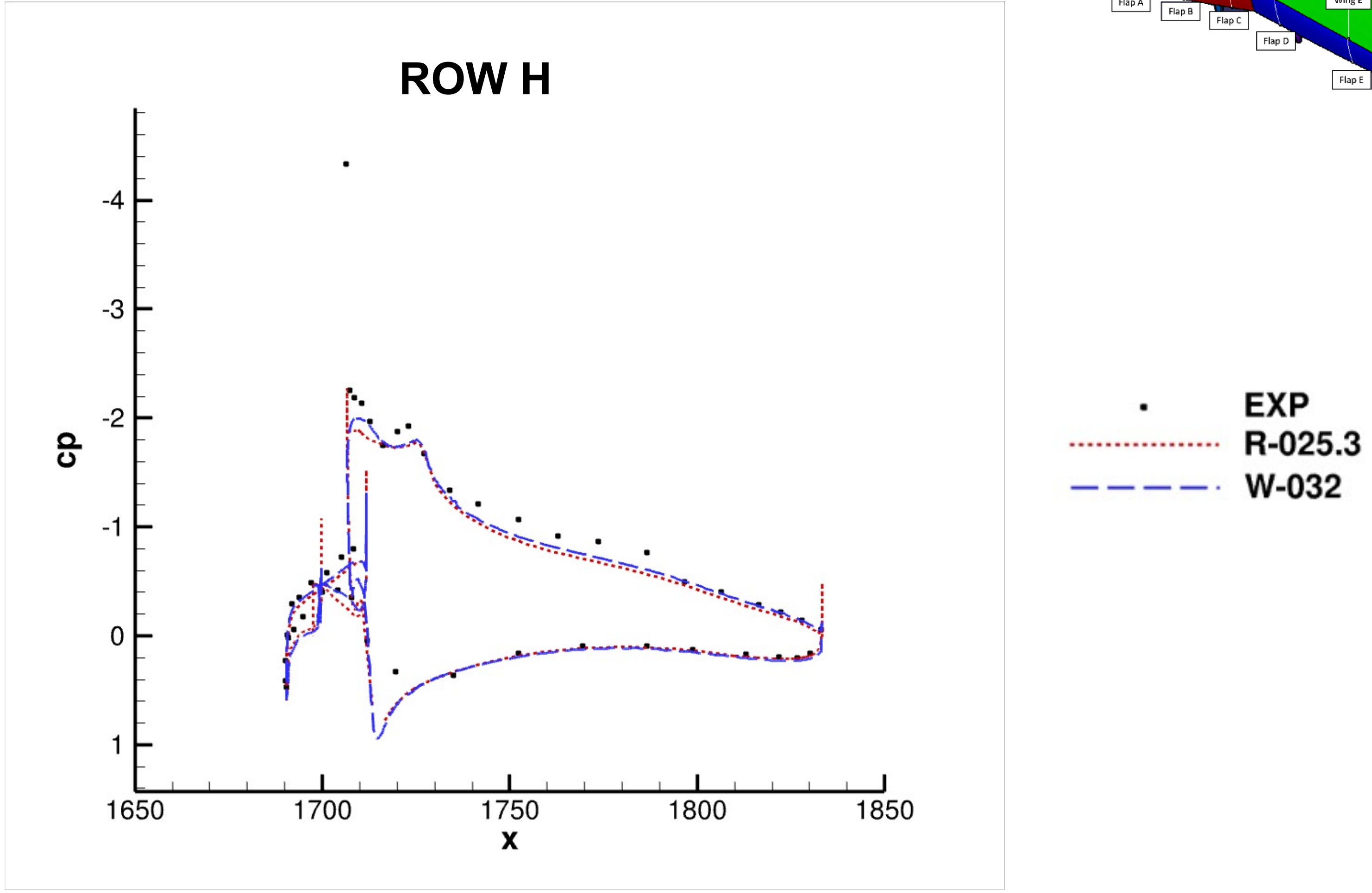


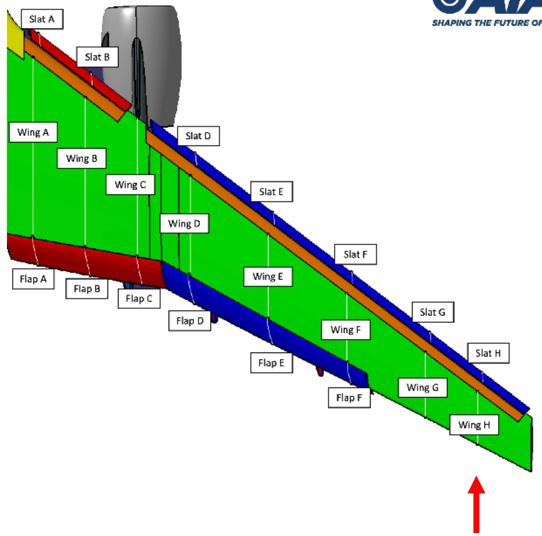


Test Case 1a – Flap Deflection Study

Comparison of Surface Pressures - Flap 40/37

W-032 shows slightly better agreement with WT test data for all elements, but both CFD results under-predict upper surface pressure distribution



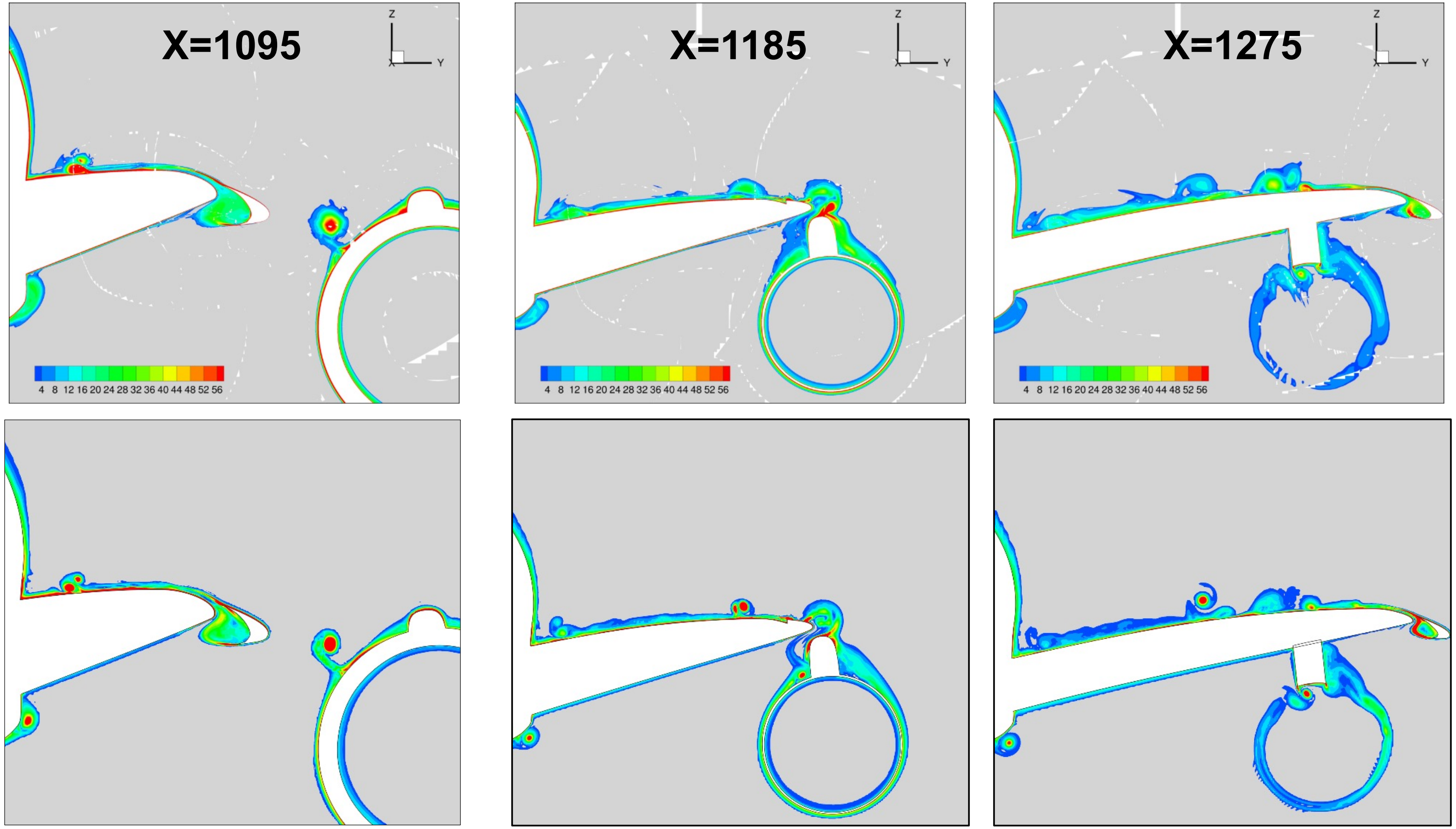


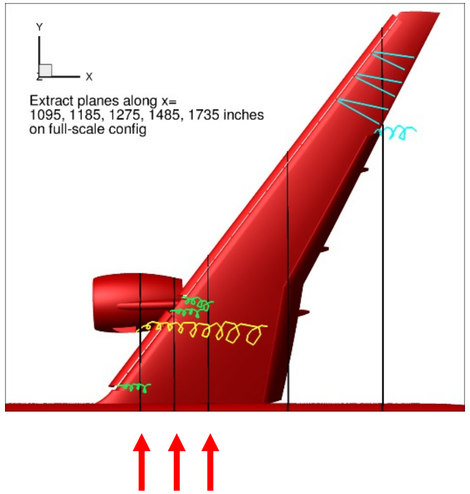
Test Case 1a – Flap Deflection Study

Comparison of Off Body Vorticity - Flap 40/37

R-025.3

W-032





W-032 shows significantly better resolved vortex structures than R-025.3 at all three streamwise locations

Test Case 1a – Summary

- Large number of RANS datasets were provided by workshop participants, including those using verified flow solvers, but limited number of results from emerging CFD methods.
- Selected (few) CFD datasets show **reasonable qualitative trends with force/moment data**, but detailed analysis shows **reduced levels of suction on all elements**, particularly at LE peaks, and generally **inconsistent prediction of flap separation** at all flap detents.
- Good agreement of surface pressures between selected CFD results and test data at Row A suggests that **free-air simulations are appropriate.**
- **Higher resolution of vortex structures** in W-032 may help explain better comparison of upper surface pressure distributions with test data compared to R-025.3
- Although limited test data was available, this test case was **effective in exposing modeling deficiencies** in current and next-generation CFD toolsets.

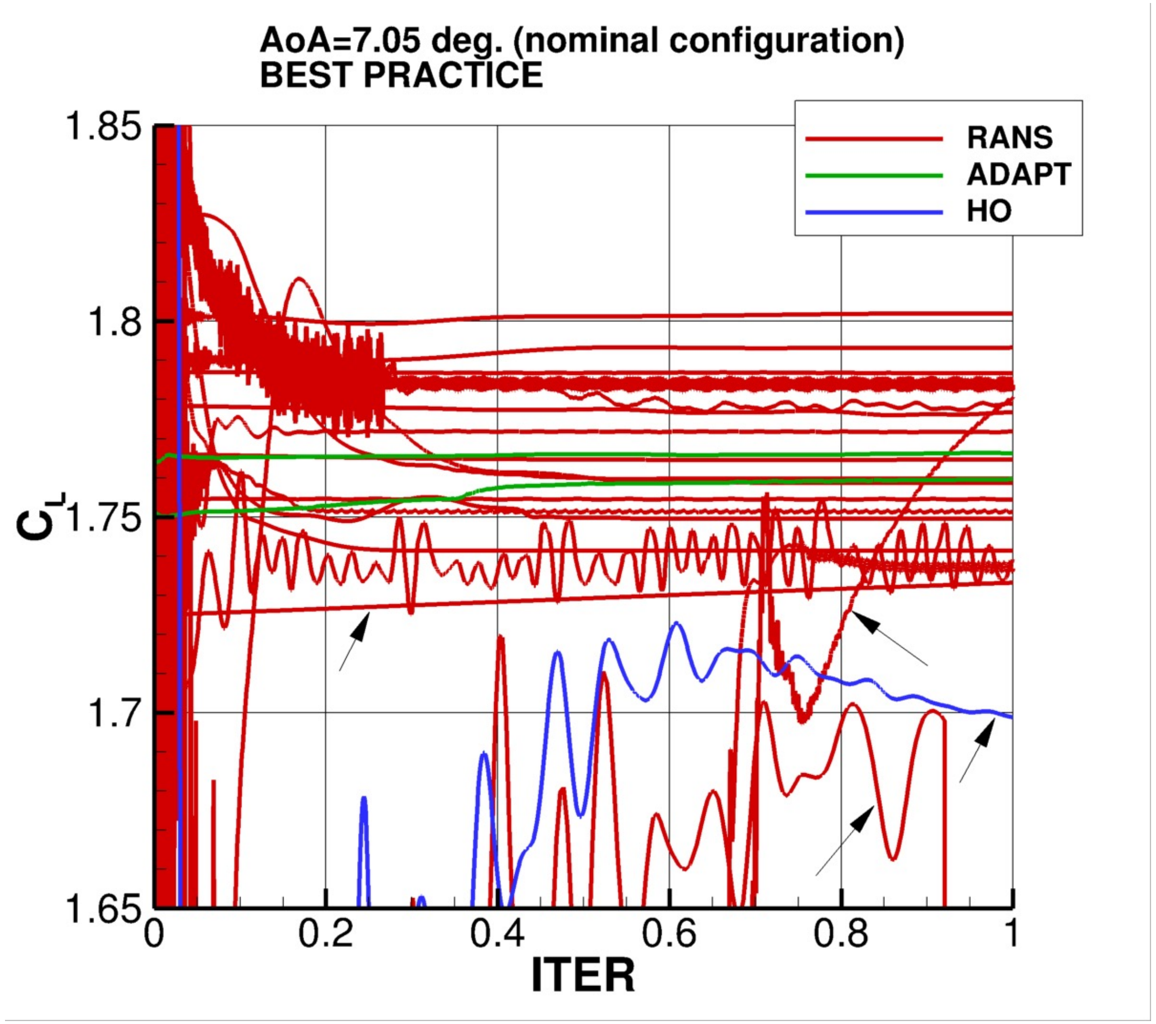
KQ#1, Iterative convergence analysis

Iterative Convergence

- Objective
  - Examine iterative convergence of CFD results
  - Focusing only on Best Practice results from RANS, ADAPT, and HO
- Background
  - In previous workshops, lack of sufficient iterative convergence accounted for some of the differences between participant results
- Data Comparisons
  - Examine results for AoA=7.05 (22 participants) and 19.57 deg. (17 participants)
  - ITER was scaled to show $0 \rightarrow 1$ (0 indicates start of recorded data, 1 indicates end of recorded data)
  - Data taken from Case 2a in most cases
    - (Case 1 used for AoA=7.05 deg. if 2a not available)
  - Several participants did not submit iterative convergence data
- Findings

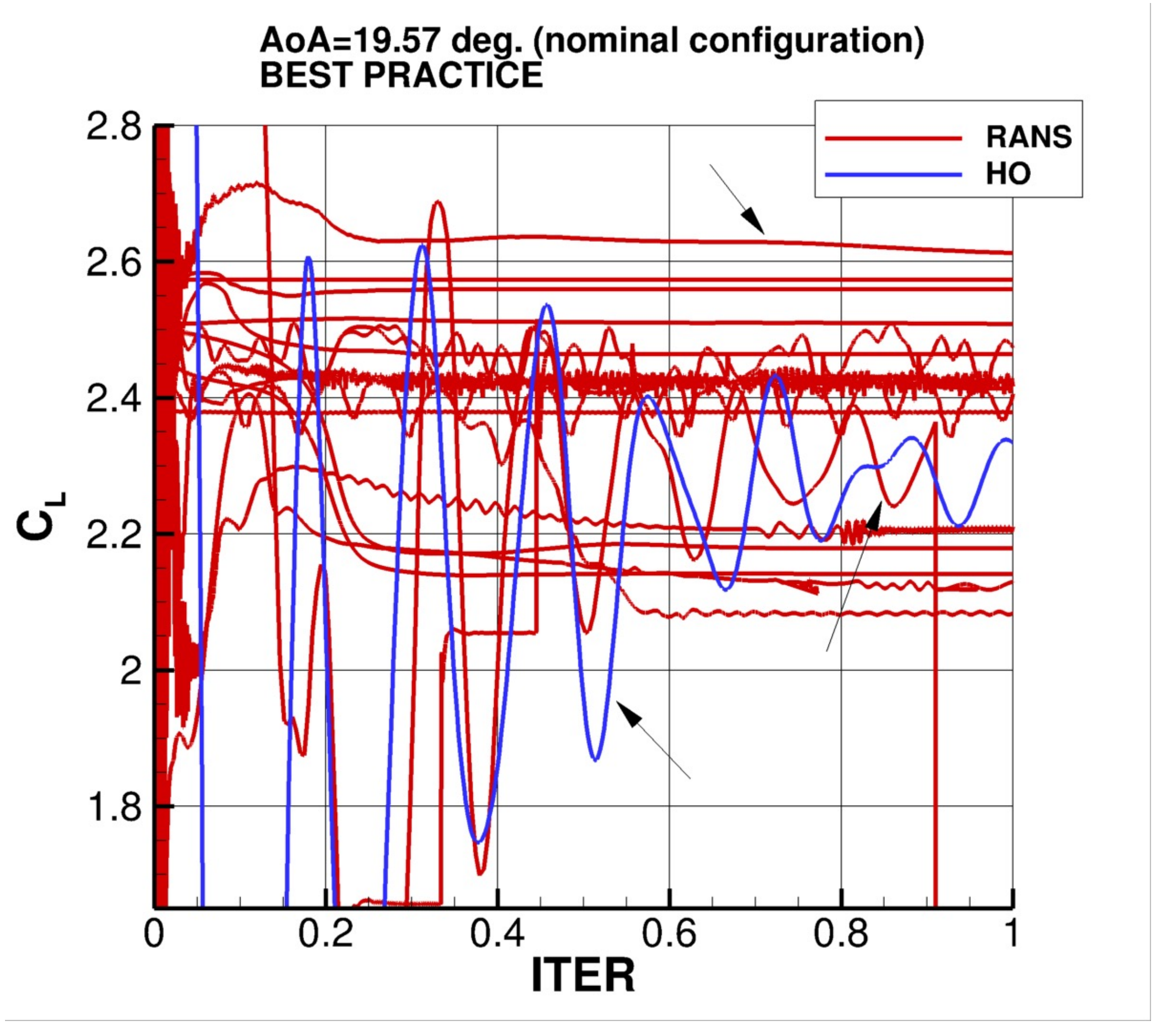
AoA = 7.05 deg.

- Many results were reasonably steady:
  - R-008.1, R-011.1, R-015.1, R-034.1, R-037.3, R-043.1, R-043.4, R-054.1, R-059.4, A-002, A-031
- Many results were unsteady, but their average appeared to be *relatively* flat:
  - R-004.1, R-009.2, R-011.2, R-019.2, R-025.3, R-059.3, R-060.1
- A few results showed significant slope or variation at end of run (black arrows in figure):
  - R-021.1, R-028.1, R-050, and H-012



AoA = 19.57 deg.

- Many results were reasonably steady:
    - R-008.1, R-011.1, R-011.2, R-019.2, R-025.3, R-037.3, R-043.1, R-043.4
- Many results were unsteady, but their average appeared to be *relatively* flat:
    - R-009.2, R-034.1, R-054.1, R-059.3, R-059.4, R-060
- A few results showed significant slope or variation at end of run (black arrows in figure):
    - R-028.1, R-050, and H-012



Iterative Convergence – Summary

- Using RANS, the C_L convergence experience varied widely at both AoAs plotted here:
  - 47-50% were relatively “steady”
  - 32-35% were unsteady, but their average near the end looked *relatively* flat
    - Question: should these be reporting long-time-averaged results instead of end result?
  - 17-18% appeared to be unconverged (more iterations needed)
- Perhaps future workshops should specify requirements for “adequate iterative convergence” (both steady and unsteady)

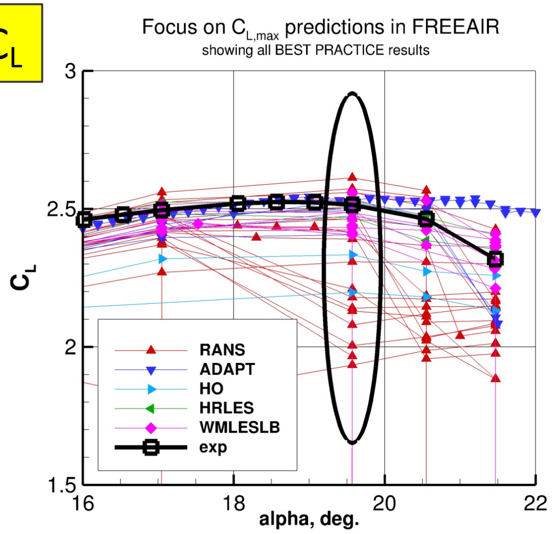
KQ#1, Test Case 2a analysis

Test Case 2a – $C_{L,max}$ Study

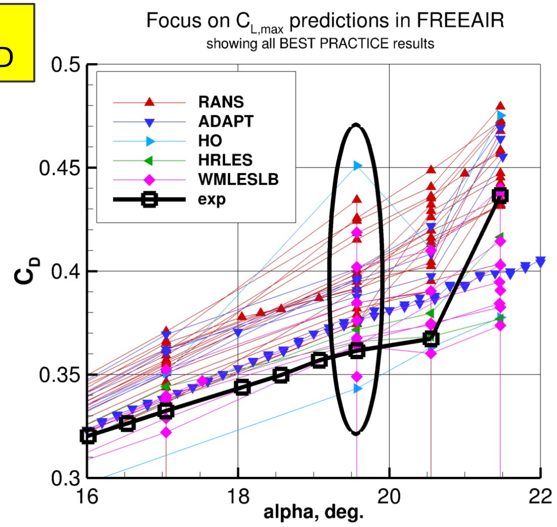
- Objective
  - Determine ability of CFD to consistently and accurately predict behavior of flowfield near $C_{L,max}$
- Background
  - Want to get the right answer (forces and moment) for the right reasons (flow physics)
  - Past HLPWs have shown RANS to perform reasonably well in linear part of lift curve, but it is inconsistent/unreliable near $C_{L,max}$
- Data Comparisons
  - Focus on force and moment comparisons along with surface flow patterns
- Findings

Test Case 2 – $C_{L,max}$ Study (free air)

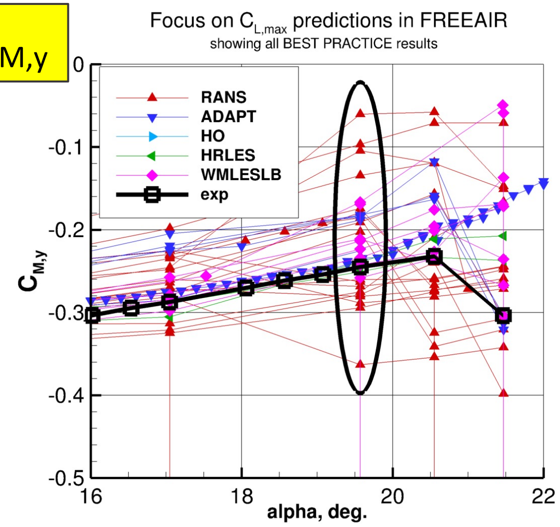
C_L



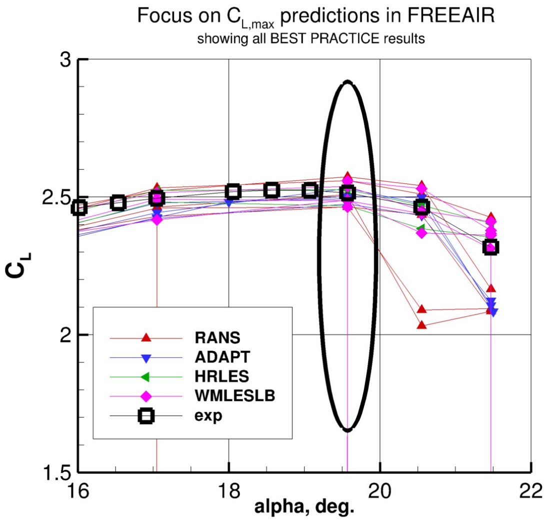
C_D

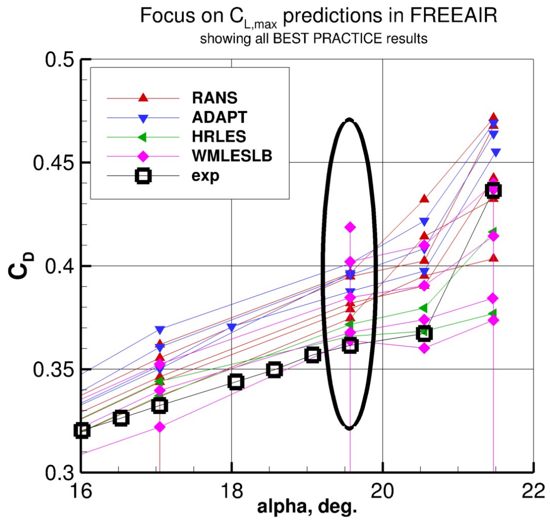


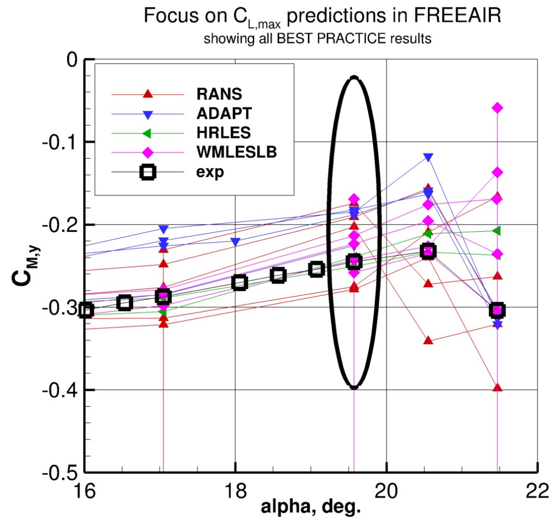
$C_{M,y}$



Pick out the results that agree best with C_L data at corrected AoA=19.57 deg.



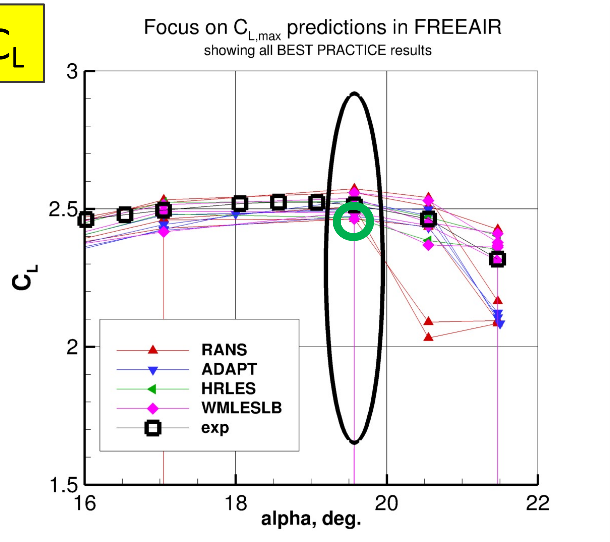




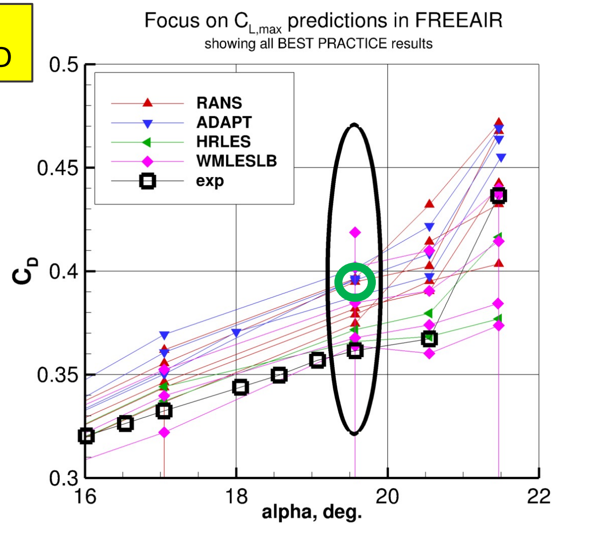
5 RANS
4 ADAPT
3 HRLES
5 WMLES

Test Case 2 – $C_{L,max}$ Study (free air)

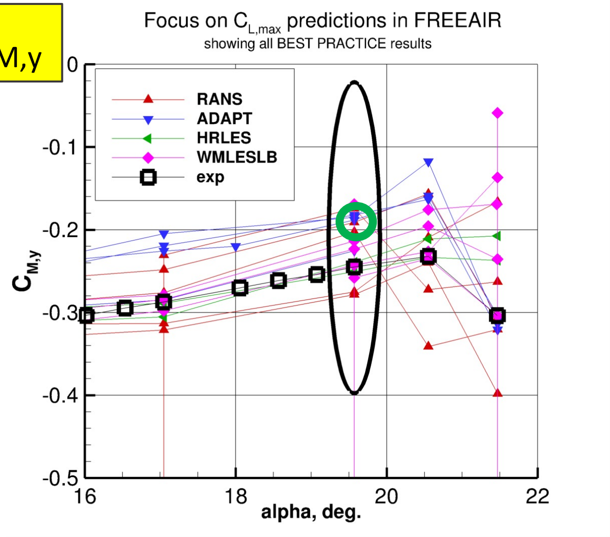
C_L



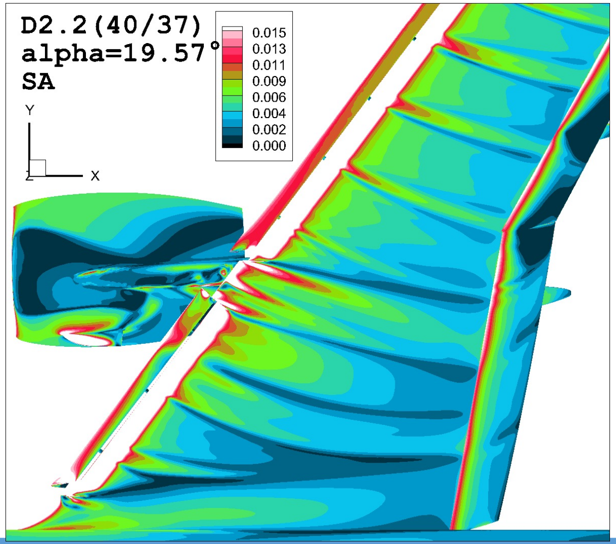
C_D

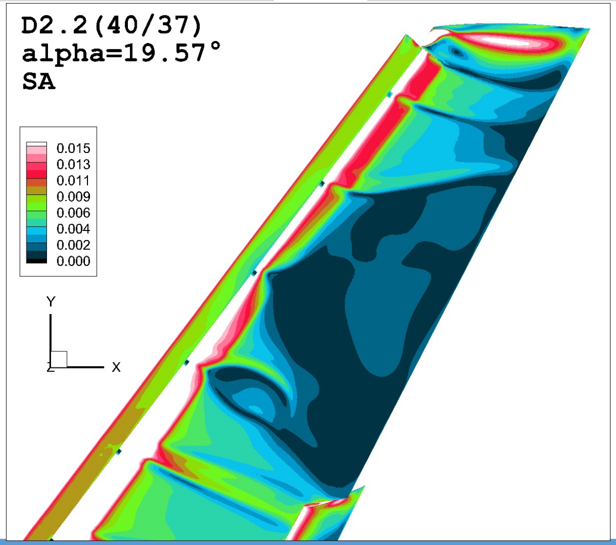


$C_{M,y}$

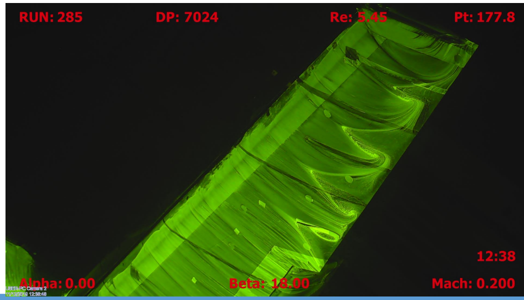


R-008.1



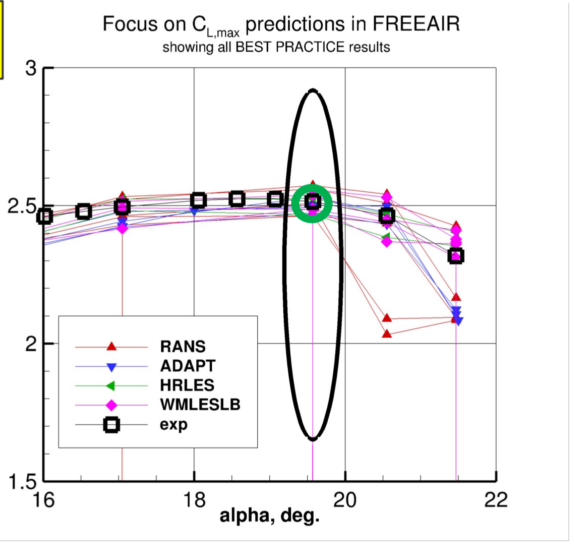


Very large outboard separation (SA model)

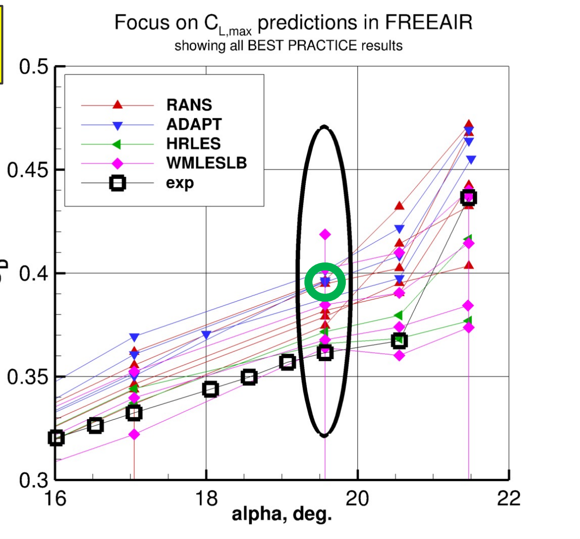


Test Case 2 – $C_{L,max}$ Study (free air)

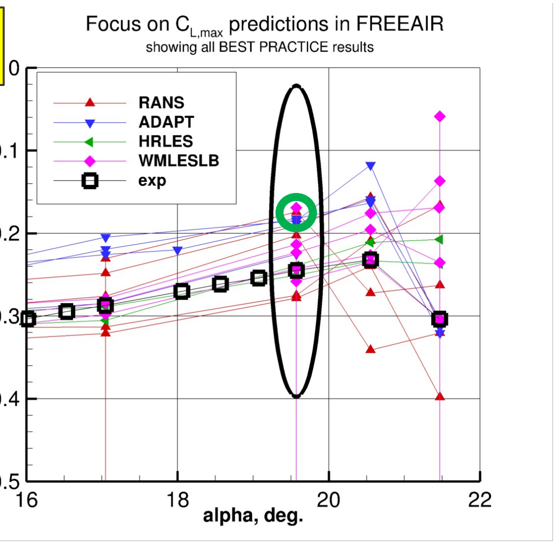
C_L



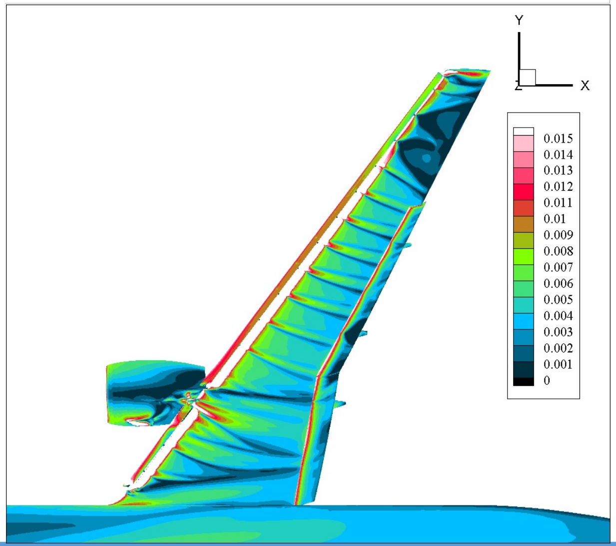
C_D



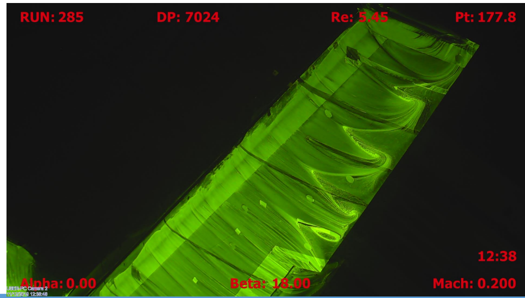
$C_{M,y}$



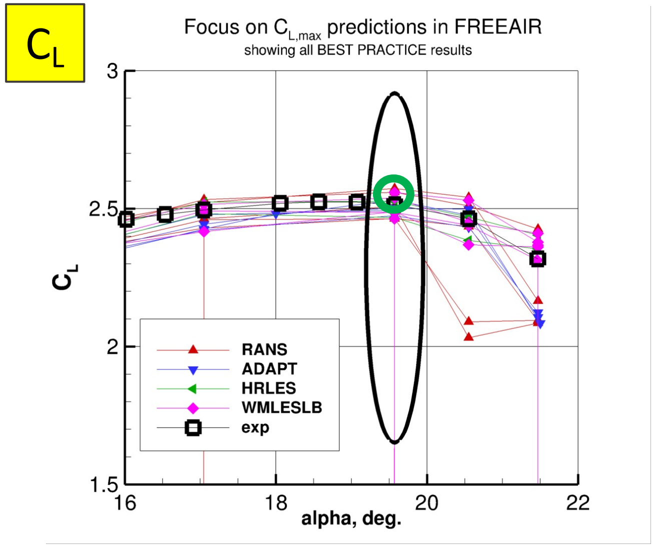
R-011.2

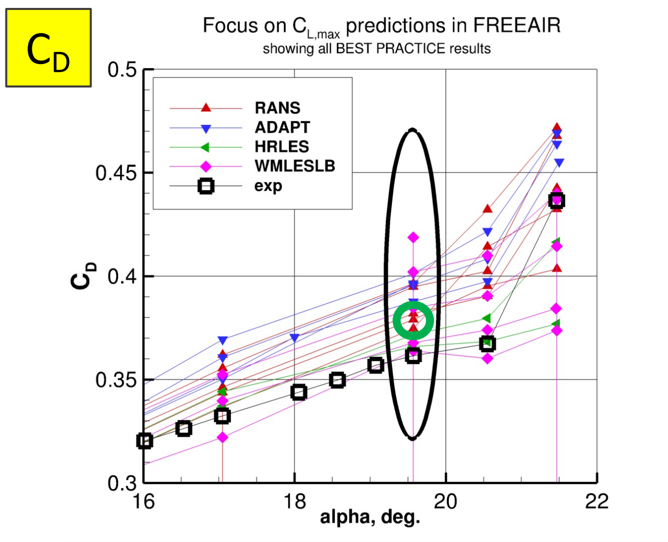


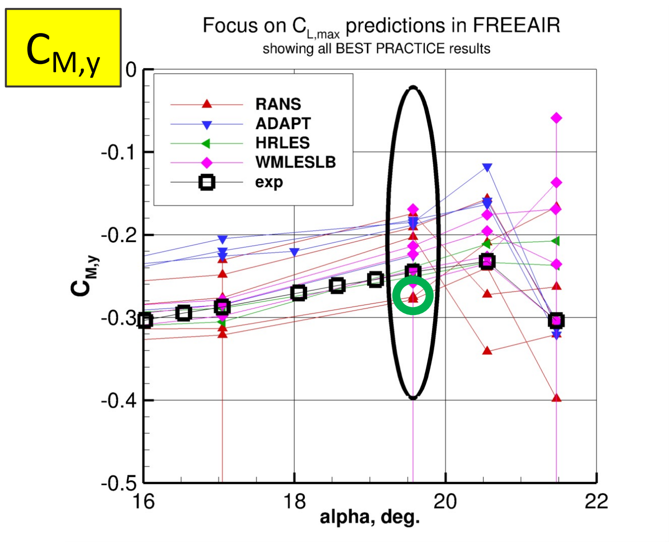
Very large outboard separation (SA model)



Test Case 2 – $C_{L,max}$ Study (free air)

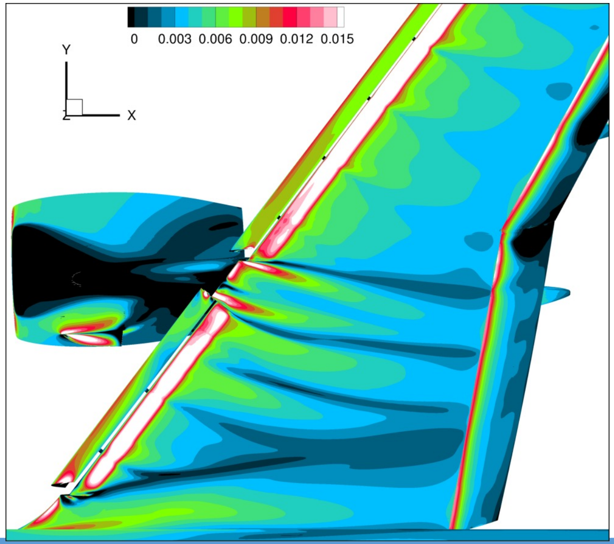


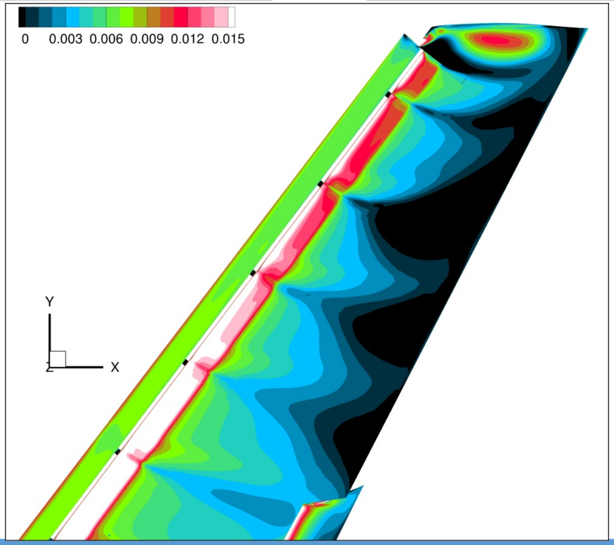




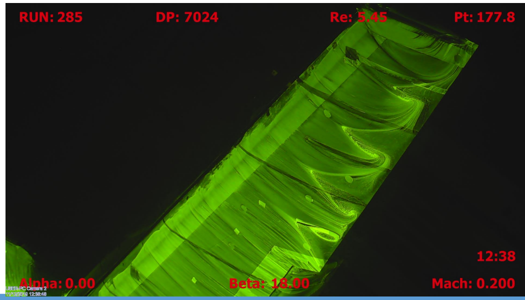
R-025.3

Note: R-025.4 (same code with finer grid) yielded similar C_L at this AoA, but outboard separation was massive like other SA RANS

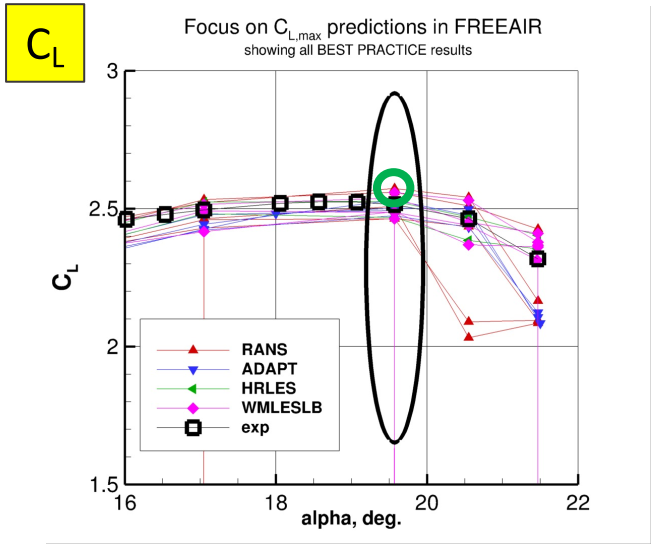


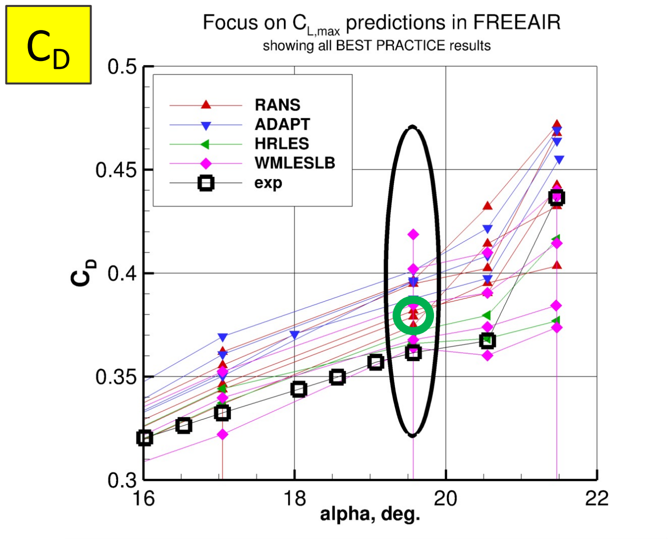


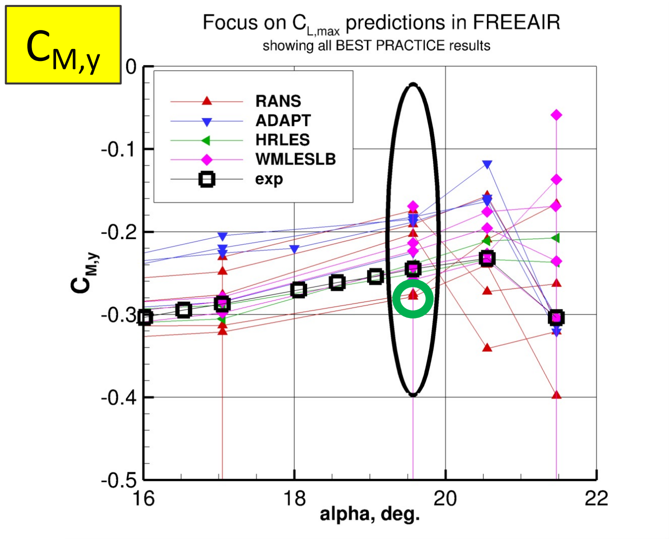
Reasonable outboard separation (SA model)



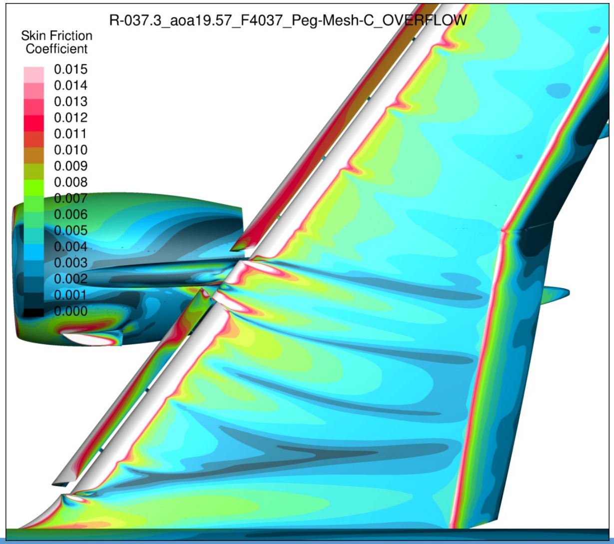
Test Case 2 – $C_{L,max}$ Study (free air)

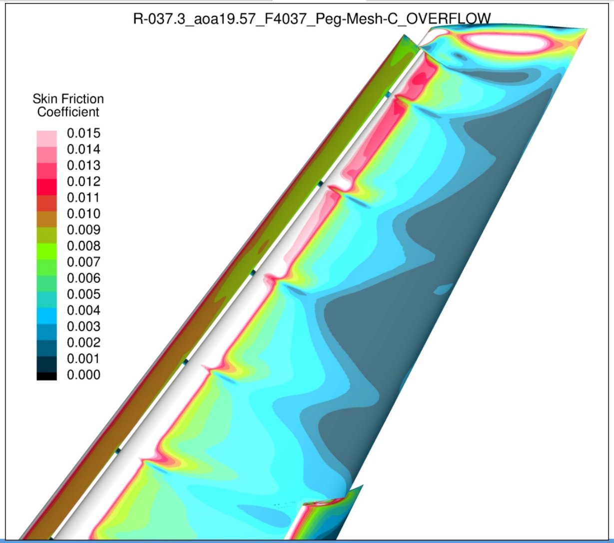




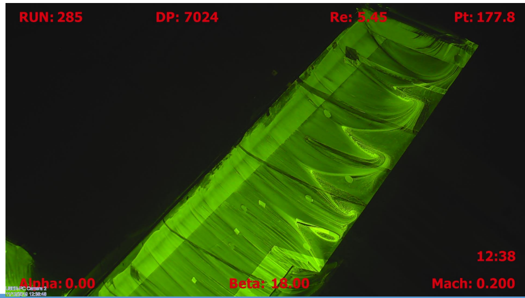


R-037.3

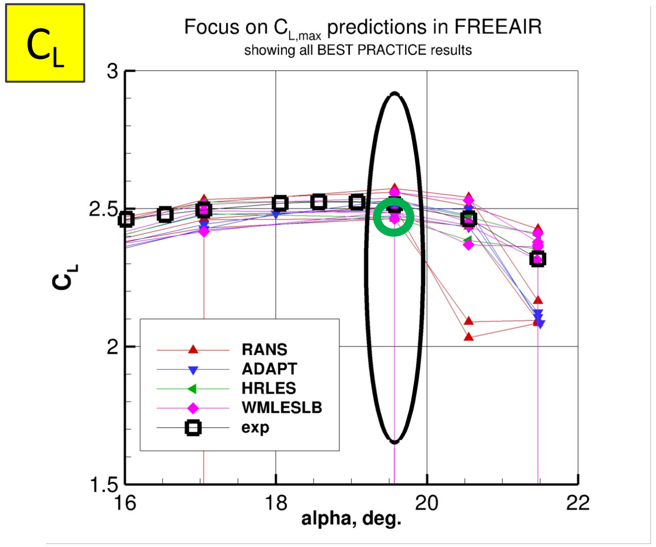


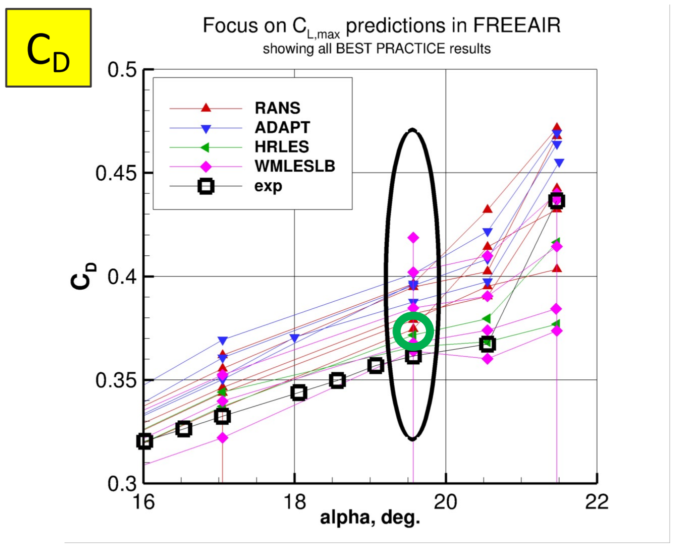


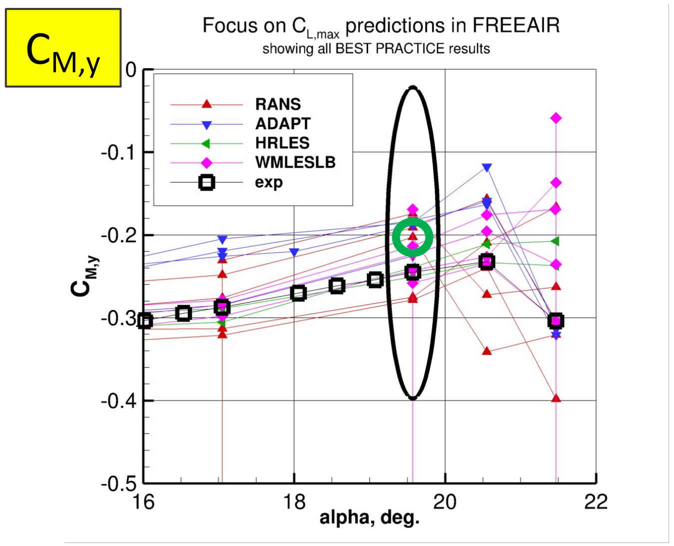
Reasonable outboard separation (SA model)



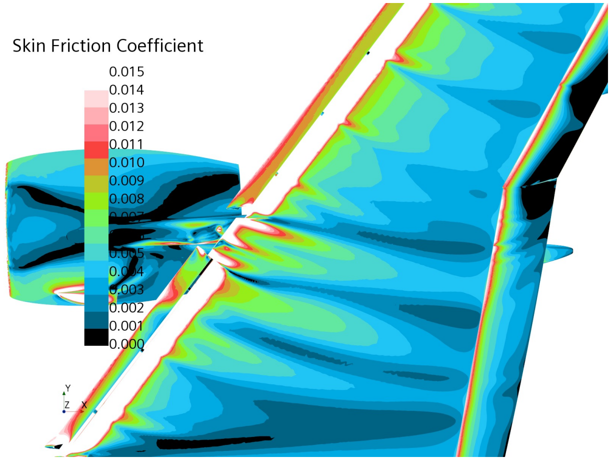
Test Case 2 – $C_{L,max}$ Study (free air)

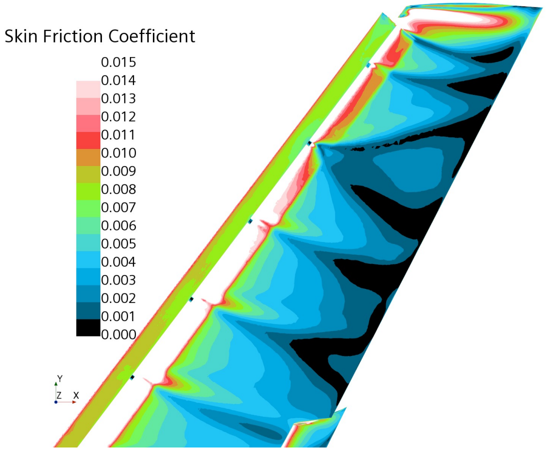




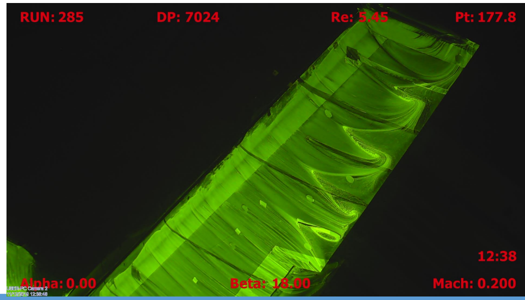


R-059.3



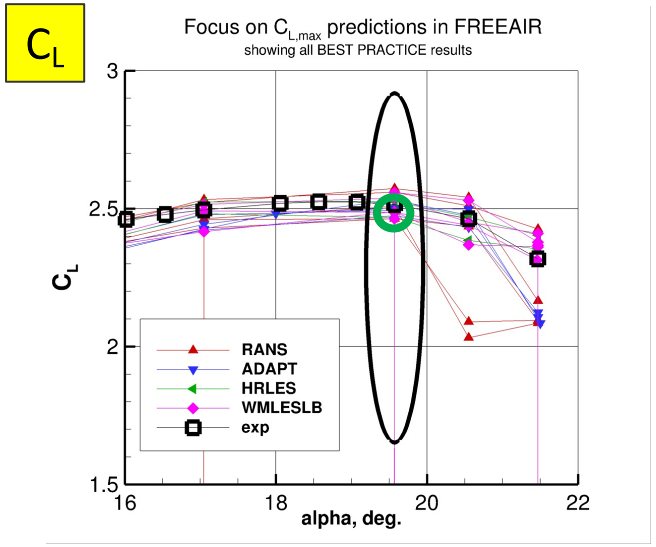


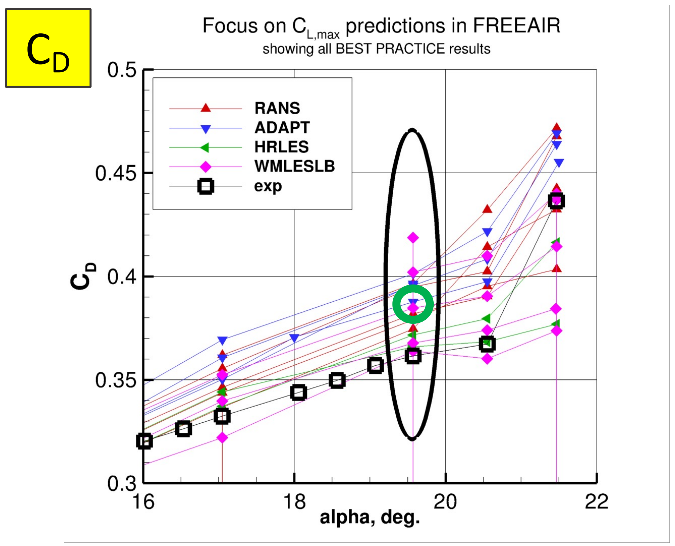
Somewhat large outboard separation (SST-a1=1 model)

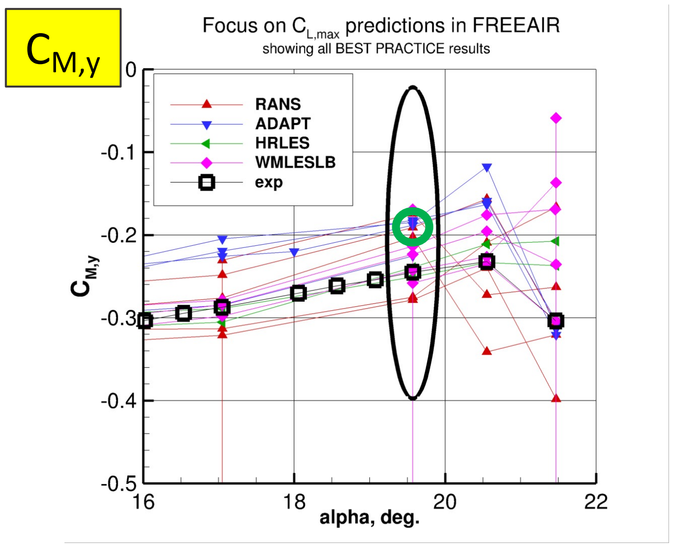


Note: R-059.4 (same code with ke-lag-EB model) yielded low C_L at this AoA with massive inboard separation, but outboard separation was reasonable

Test Case 2 – $C_{L,max}$ Study (free air)





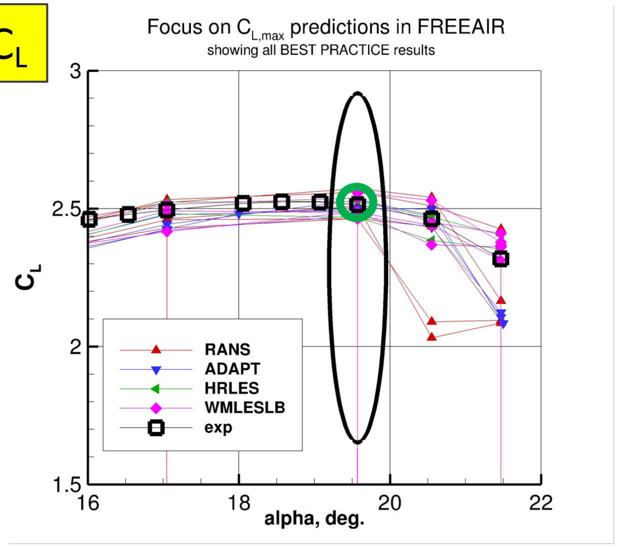


A-004.2

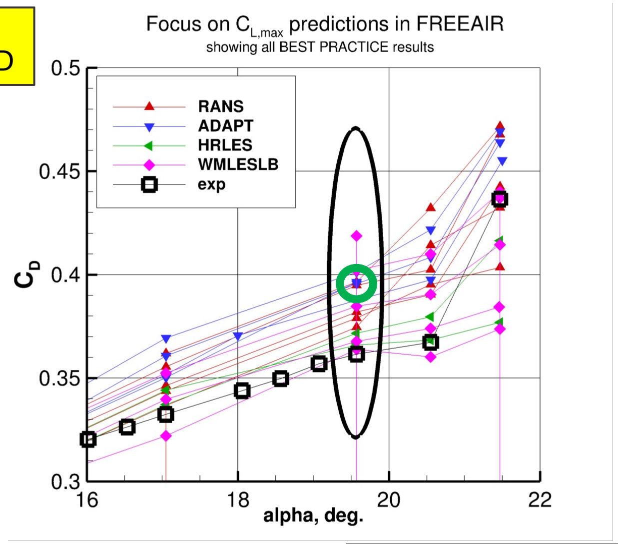
No pics provided

Test Case 2 – $C_{L,max}$ Study (free air)

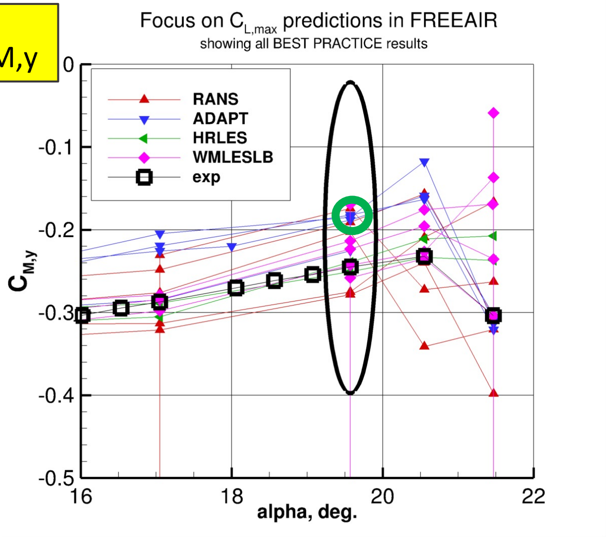
C_L



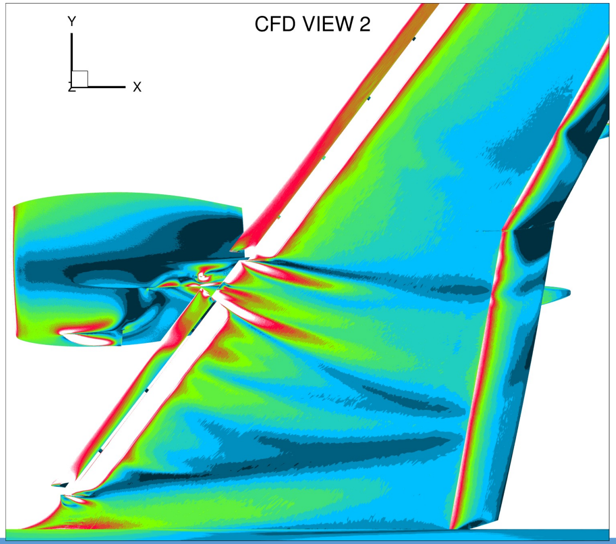
C_D

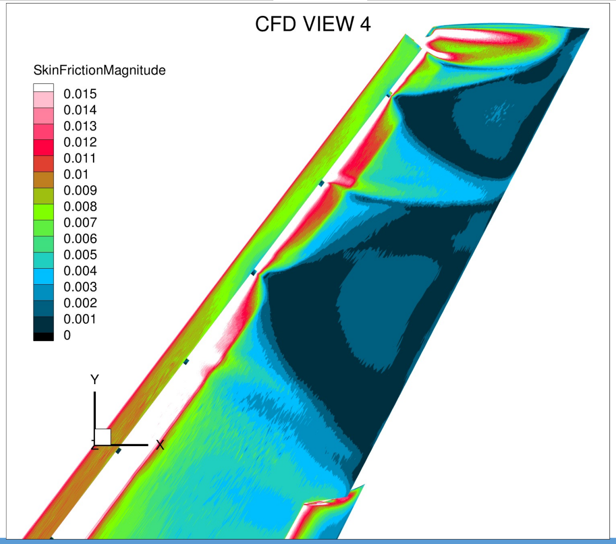


$C_{M,y}$

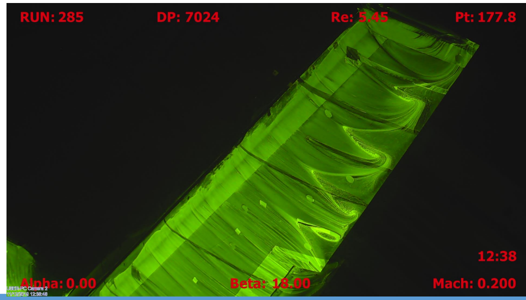


A-025.1



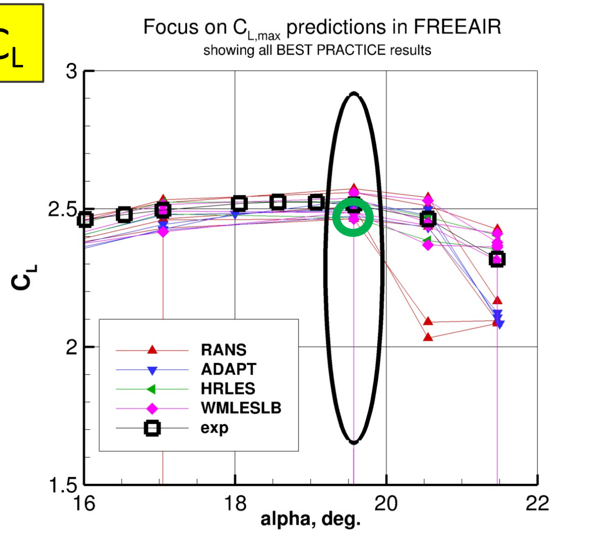


Very large outboard separation (SA model)

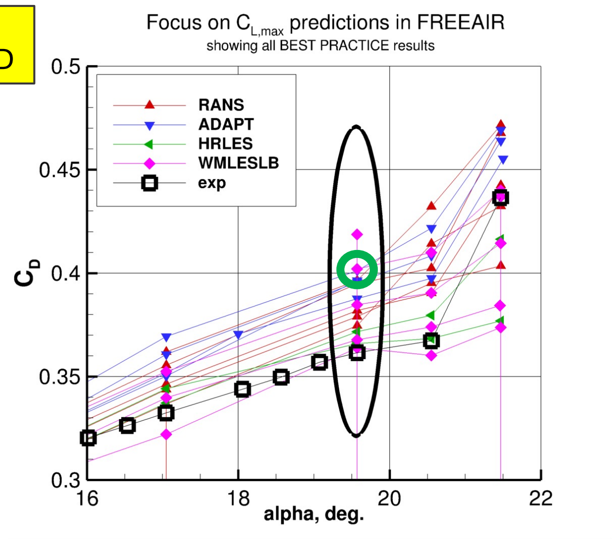


Test Case 2 – $C_{L,max}$ Study (free air)

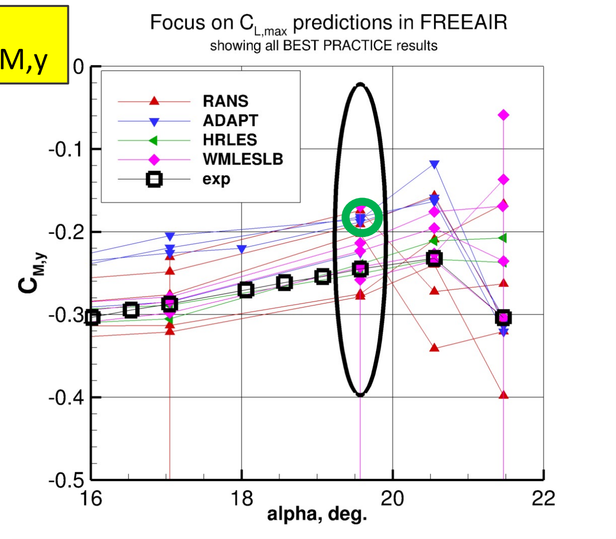
C_L



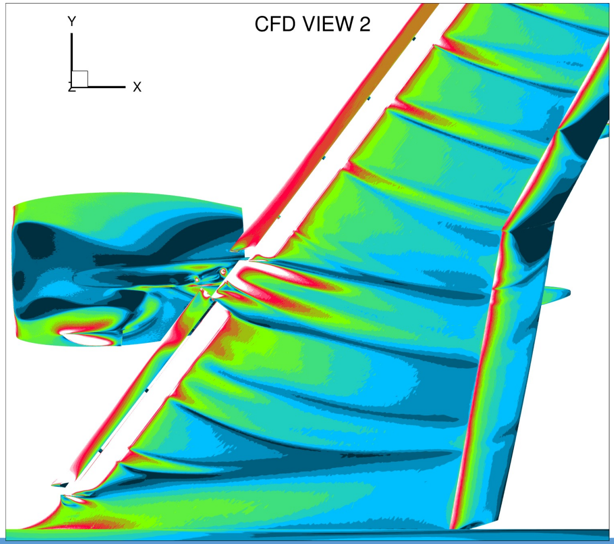
C_D

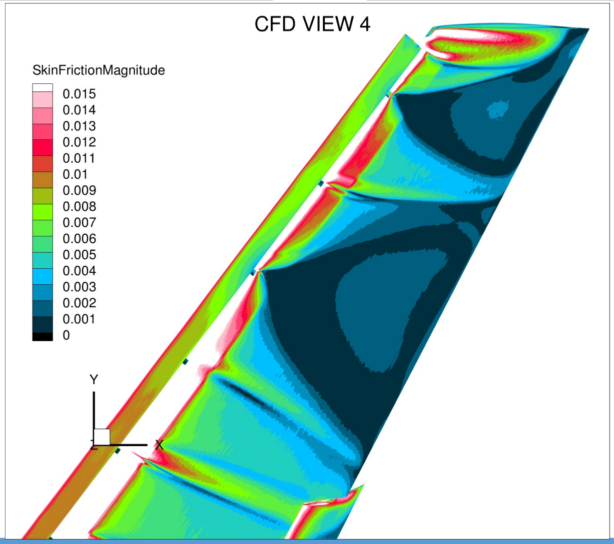


$C_{M,y}$

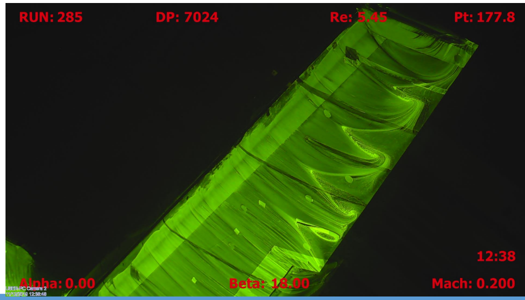


A-025.2



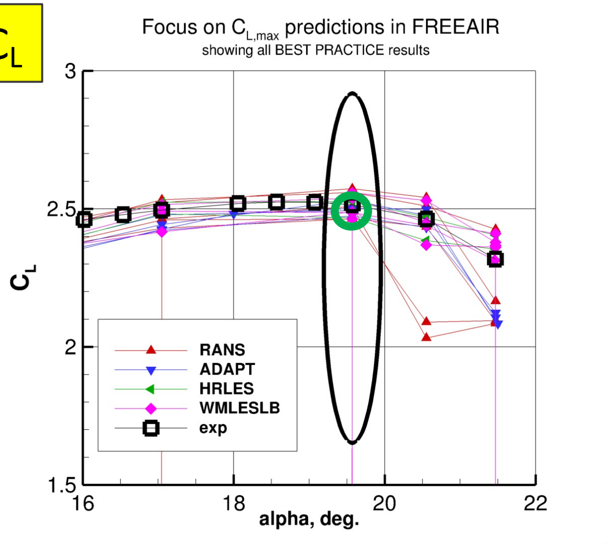


Very large outboard separation (SA model)

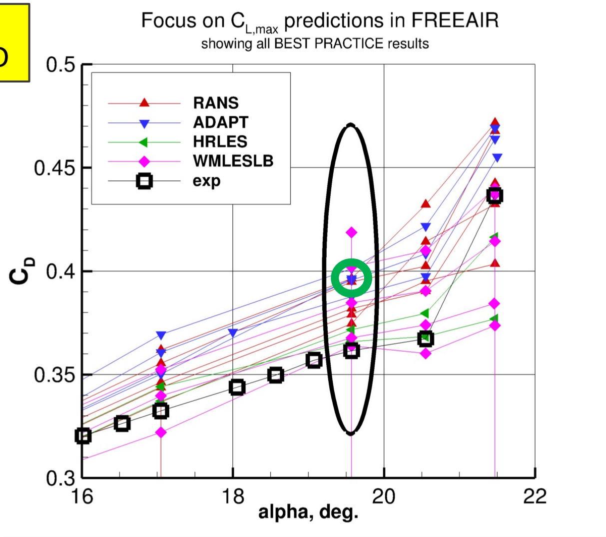


Test Case 2 – $C_{L,max}$ Study (free air)

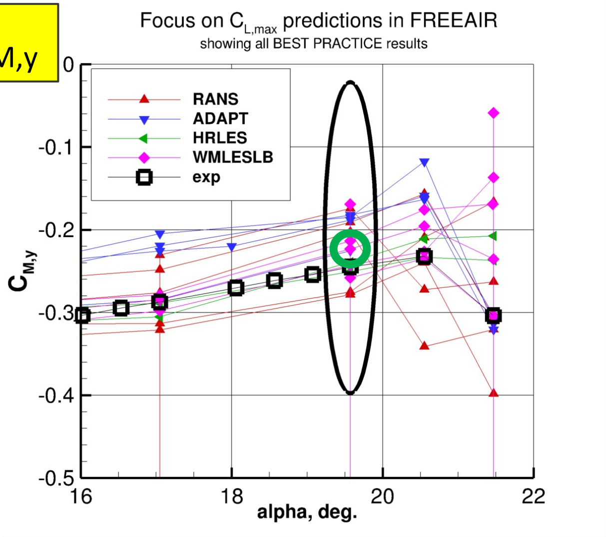
C_L



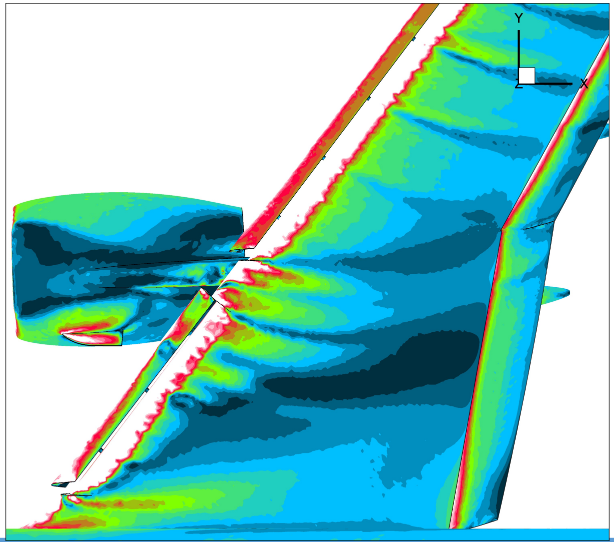
C_D

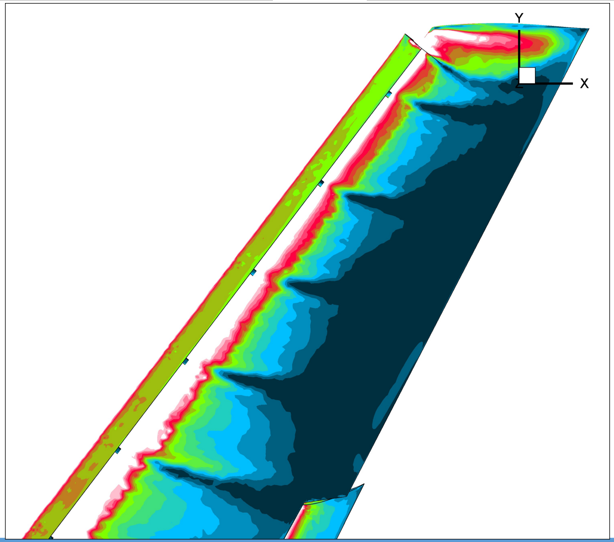


$C_{M,y}$

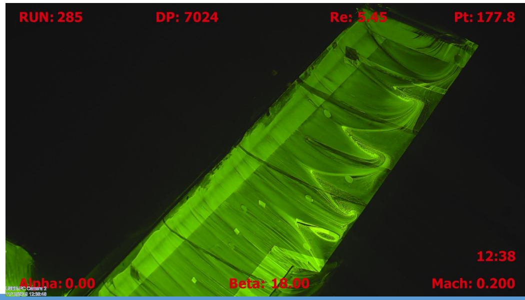


A-026



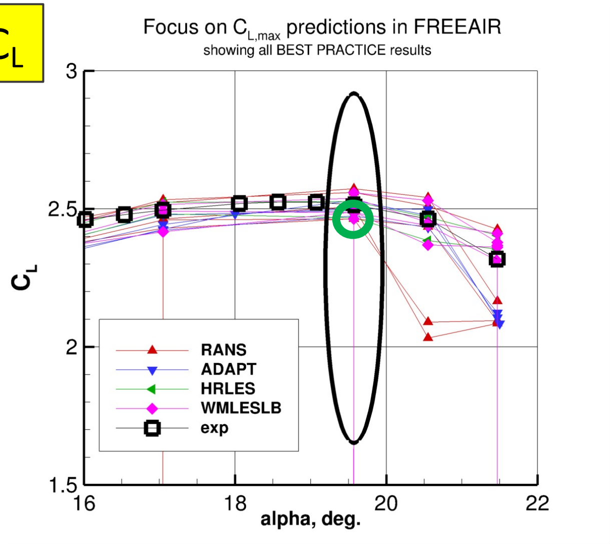


Fairly large outboard separation (SA model)

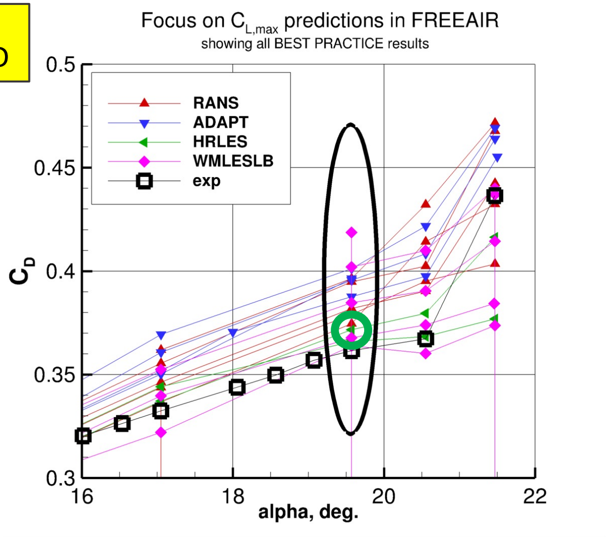


Test Case 2 – $C_{L,max}$ Study (free air)

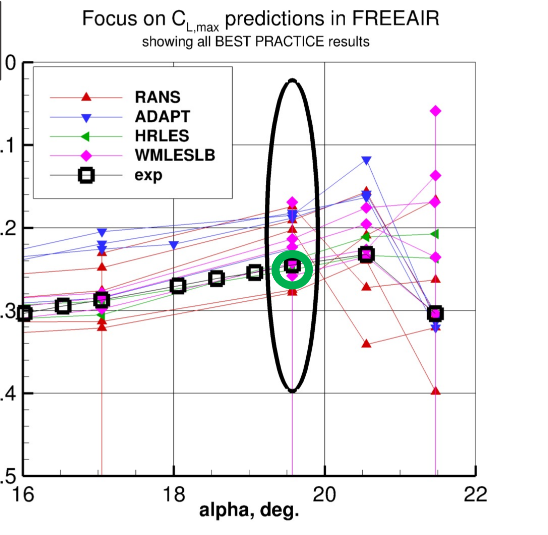
C_L



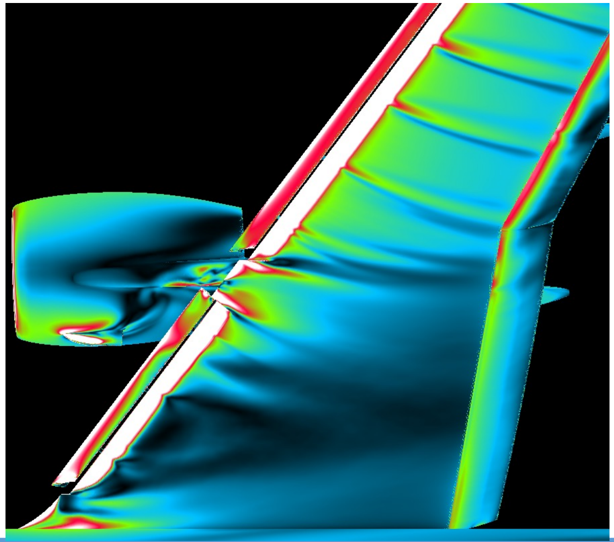
C_D

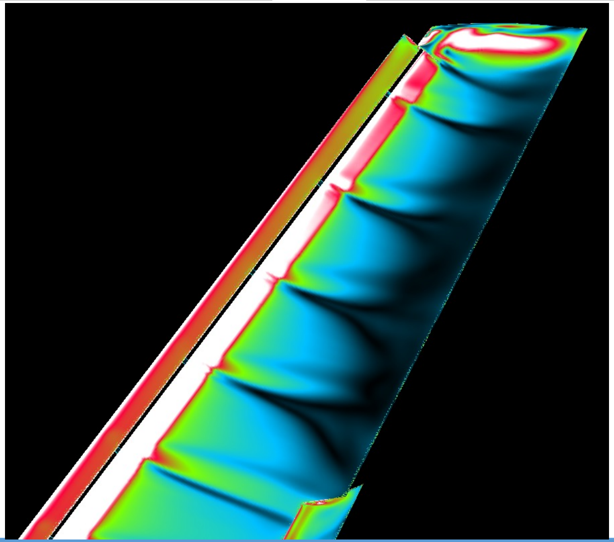


$C_{M,y}$

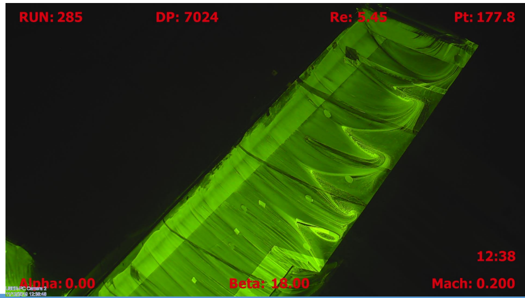


L-001.3



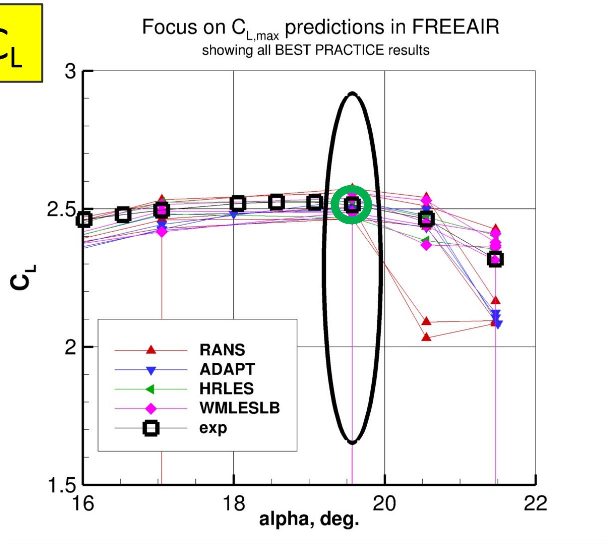


Reasonable outboard separation

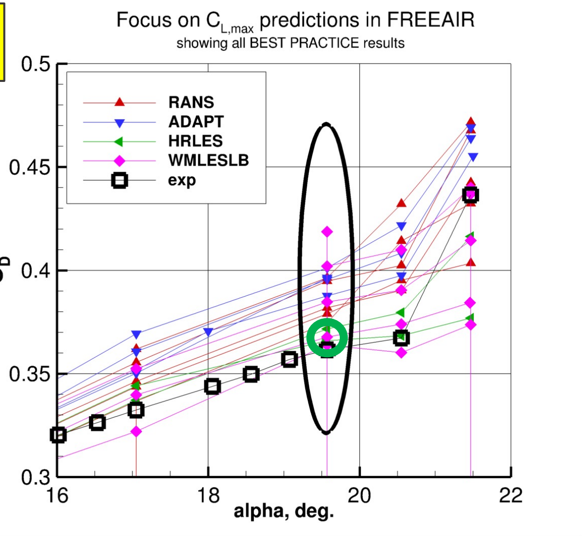


Test Case 2 – $C_{L,max}$ Study (free air)

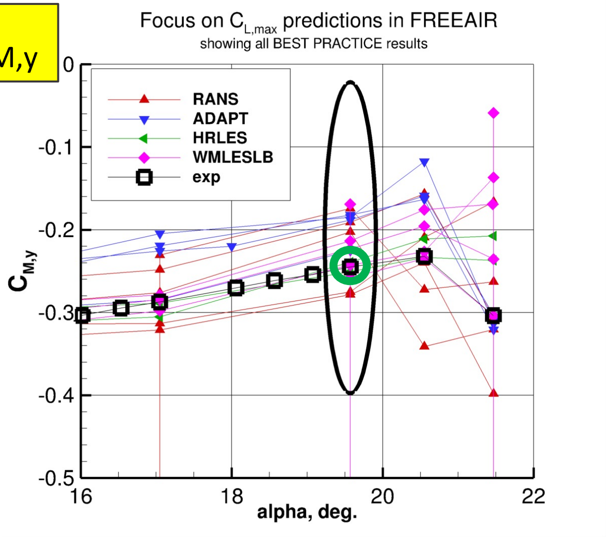
C_L



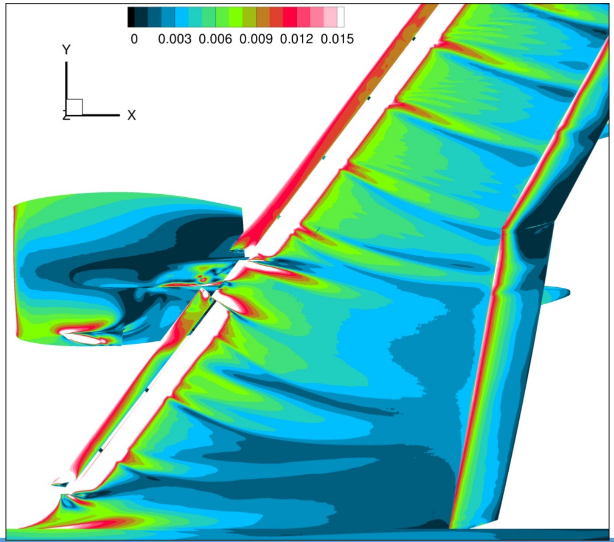
C_D

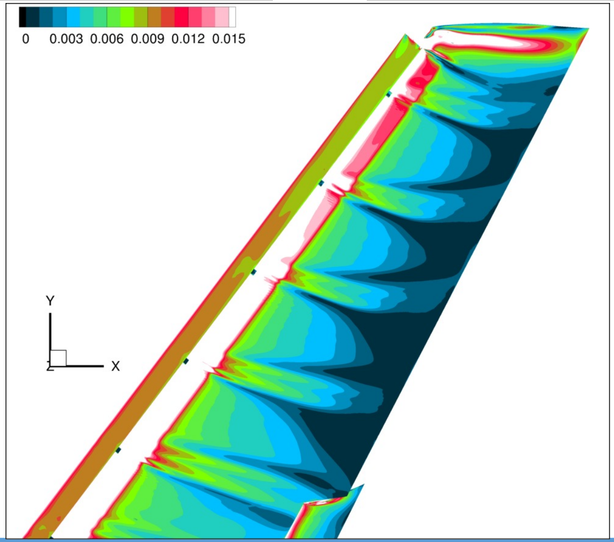


$C_{M,y}$

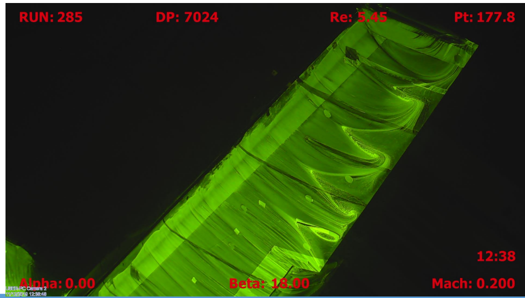


L-016.7

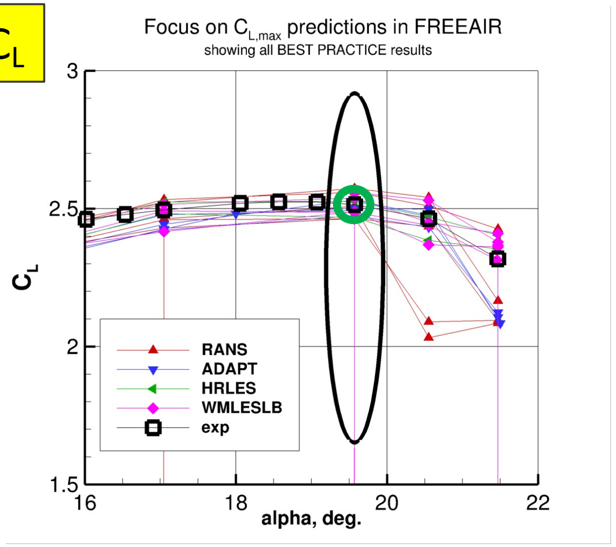


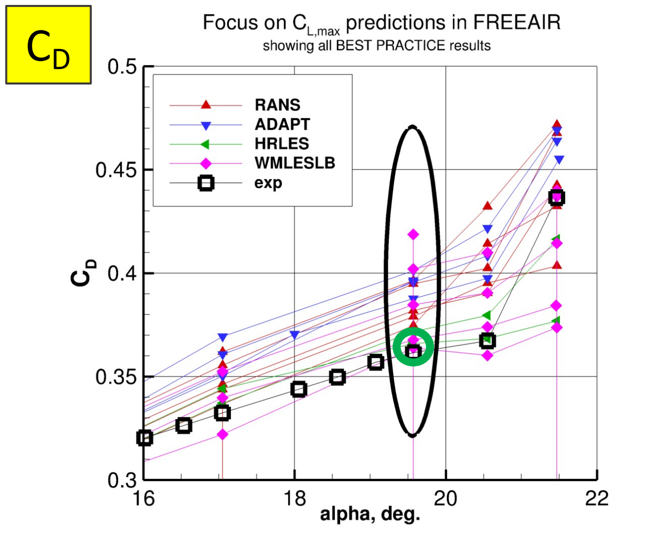


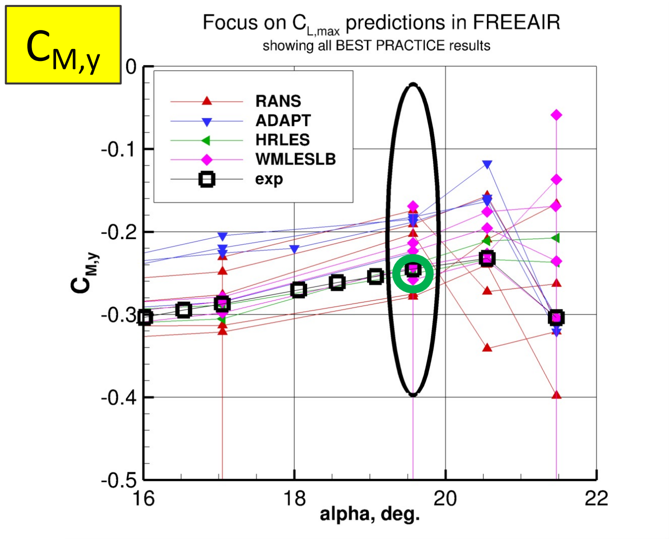
Reasonable outboard separation



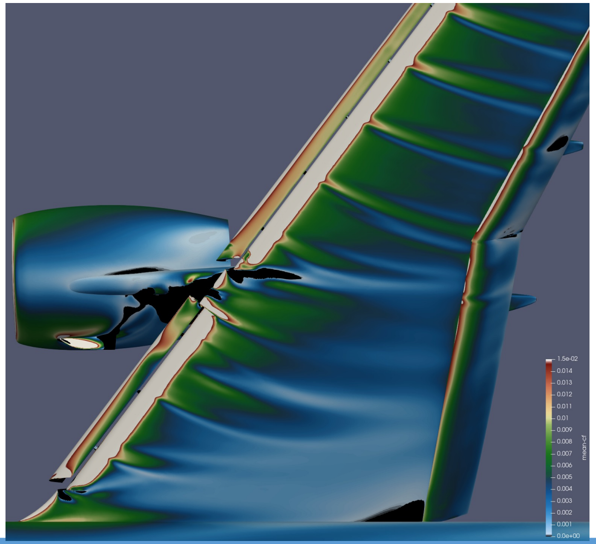
Test Case 2 – $C_{L,max}$ Study (free air)

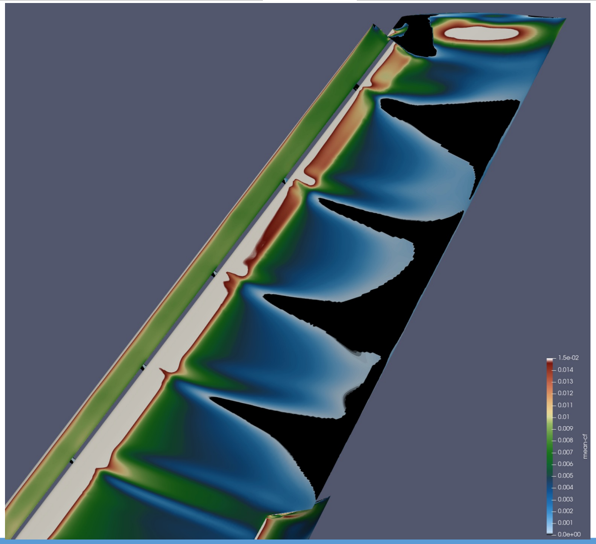




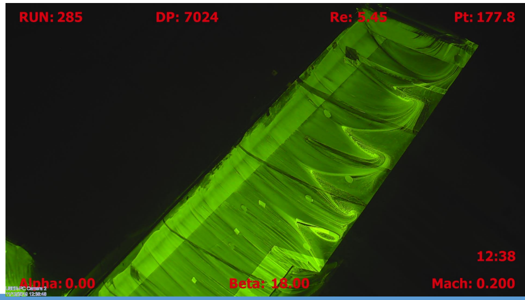


L-038

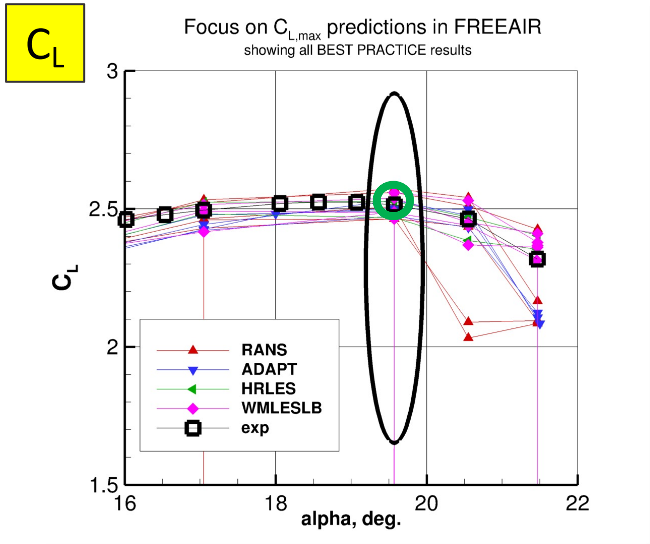


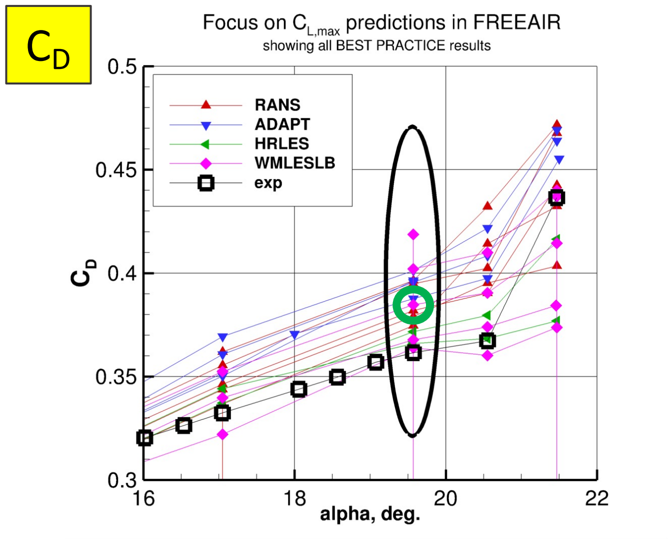


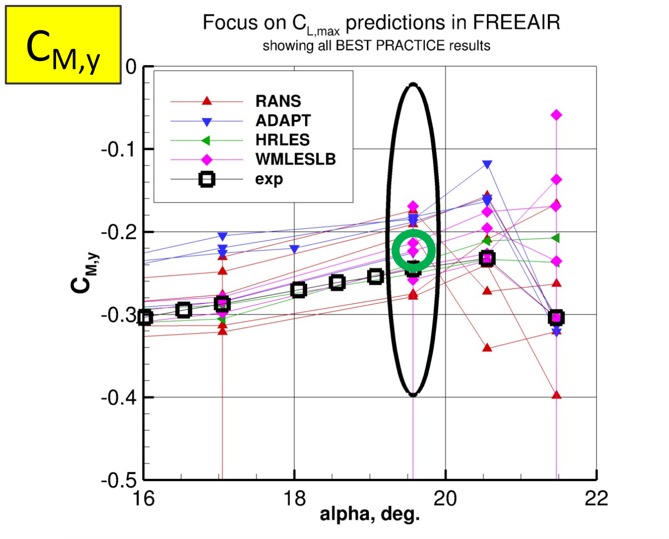
Reasonable outboard separation



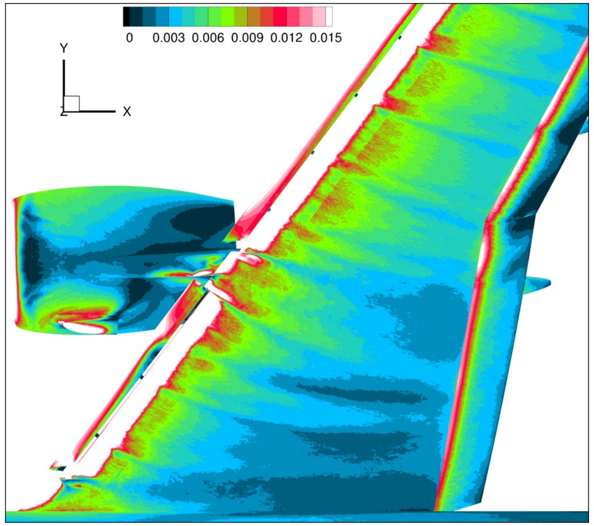
Test Case 2 – $C_{L,max}$ Study (free air)

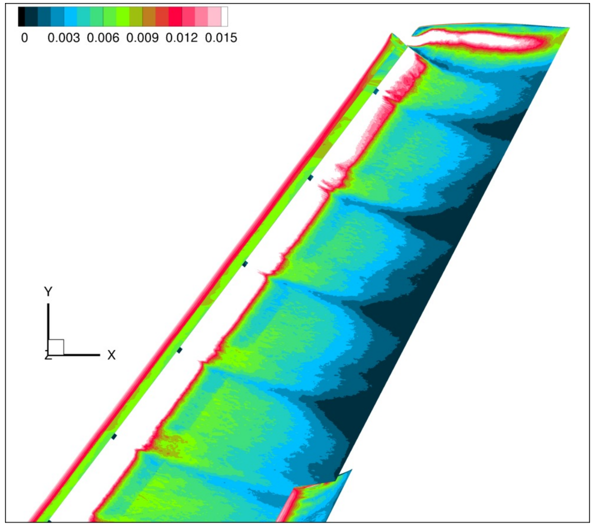




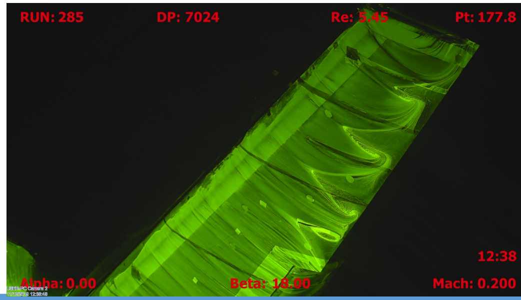


W-020.3



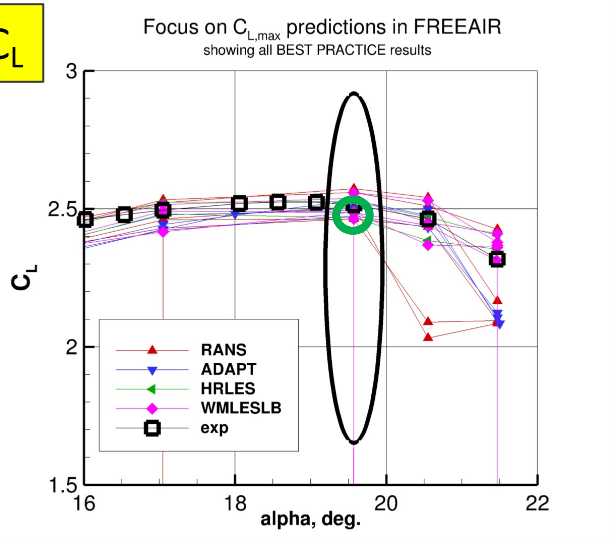


Reasonable outboard separation

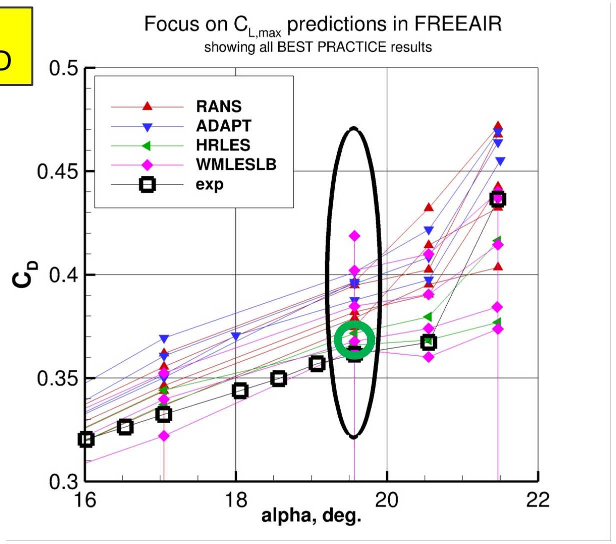


Test Case 2 – $C_{L,max}$ Study (free air)

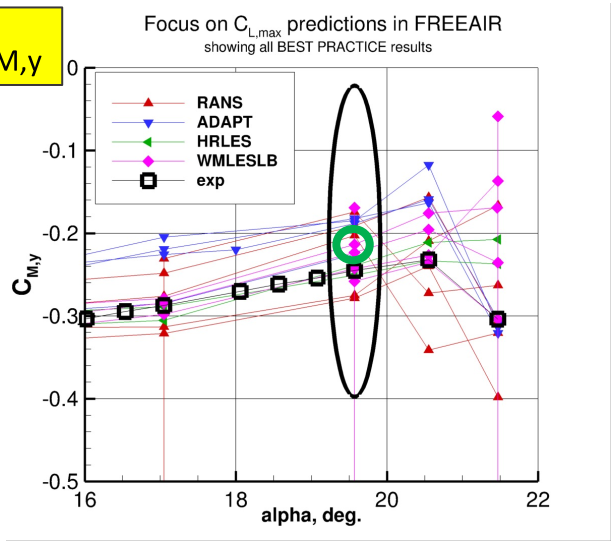
C_L



C_D



$C_{M,y}$

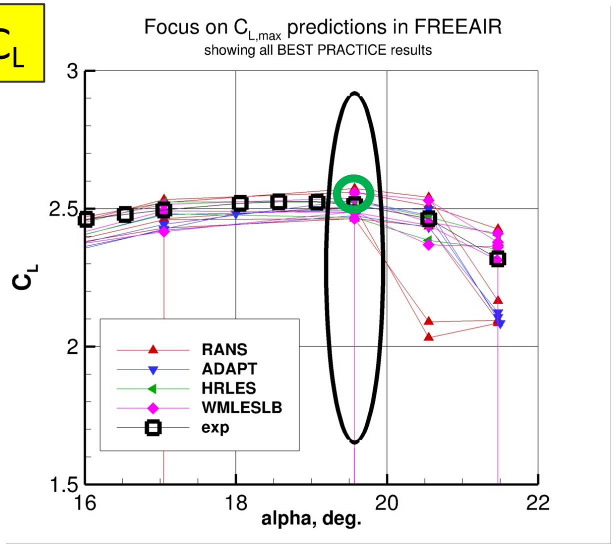


W-021.4

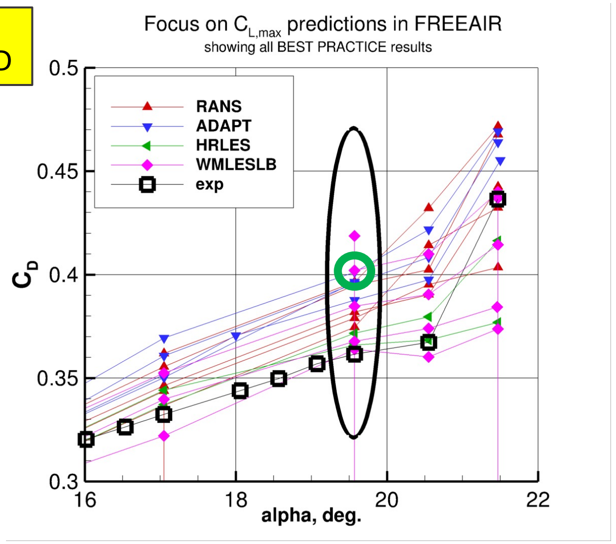
No pics provided

Test Case 2 – $C_{L,max}$ Study (free air)

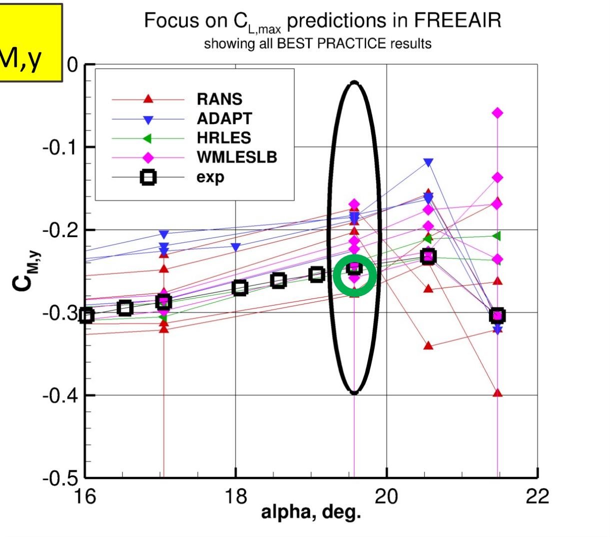
C_L



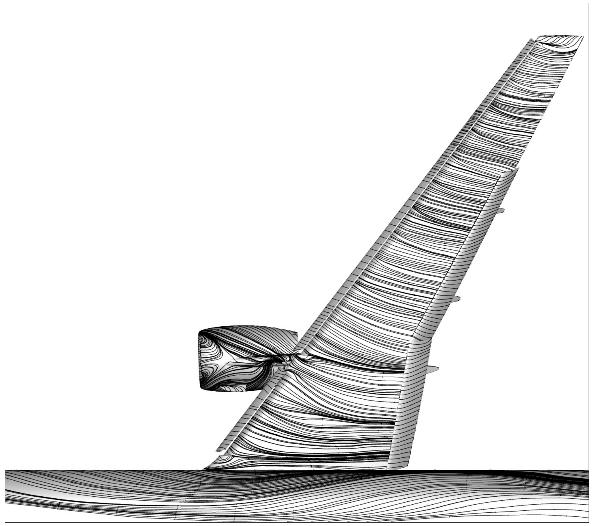
C_D

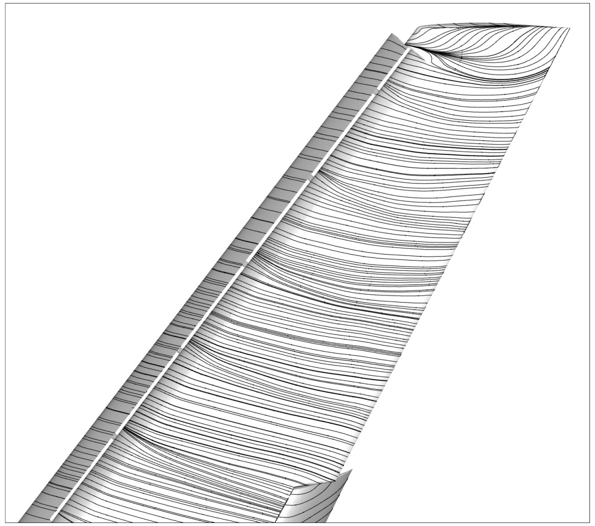


$C_{M,y}$

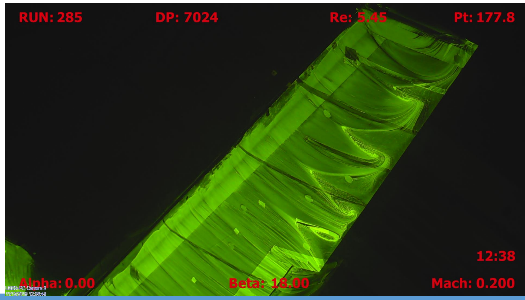


W-047

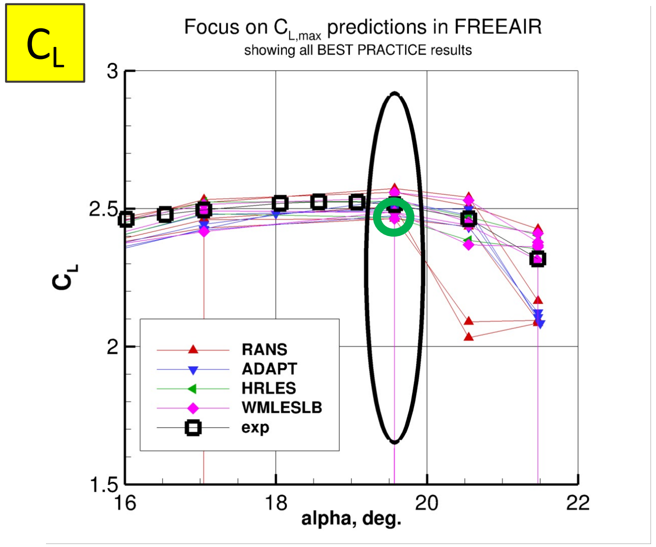


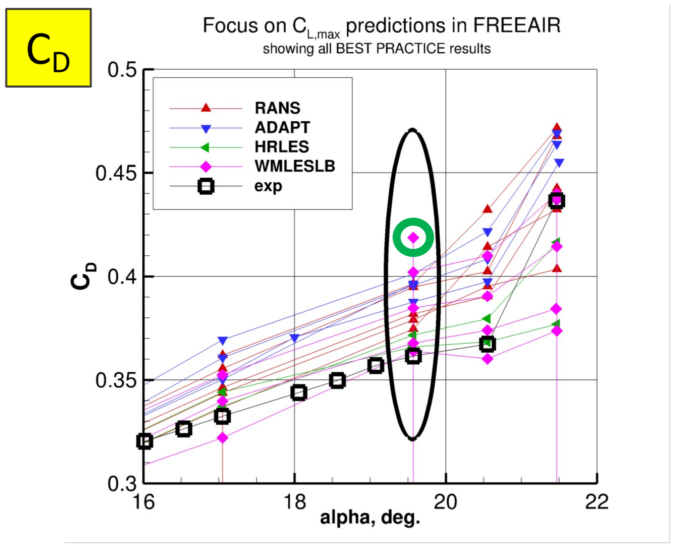


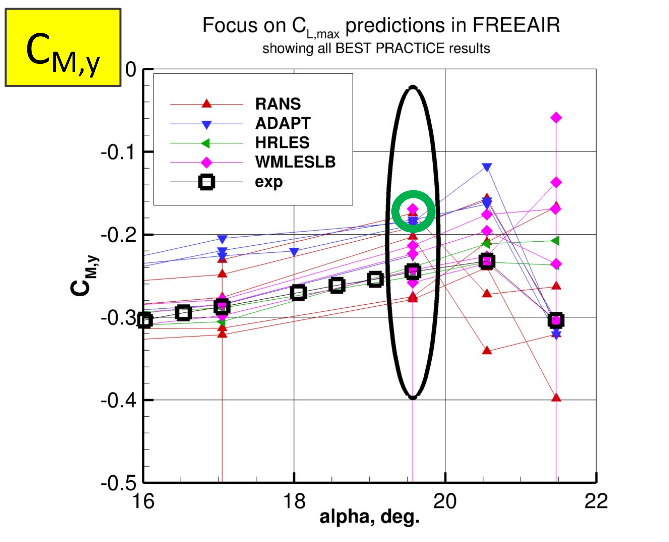
No outboard separation at all



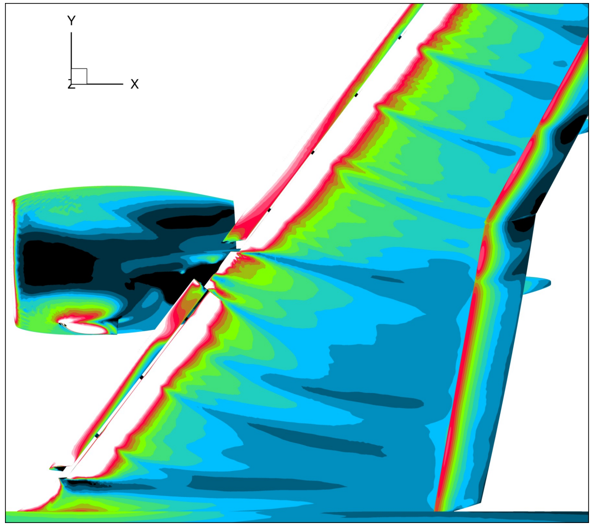
Test Case 2 – $C_{L,max}$ Study (free air)

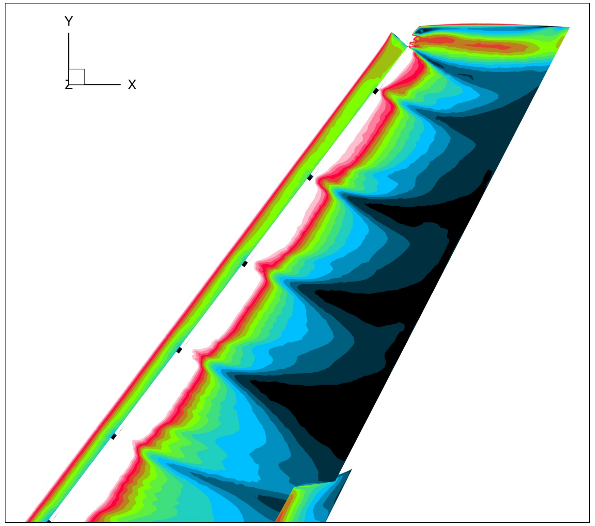




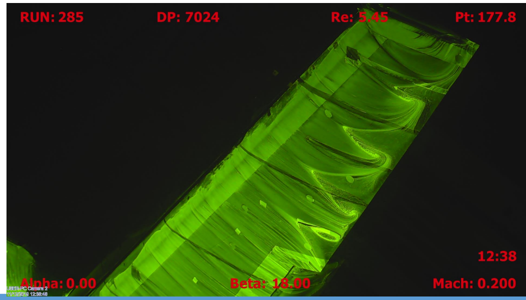


W-049.2



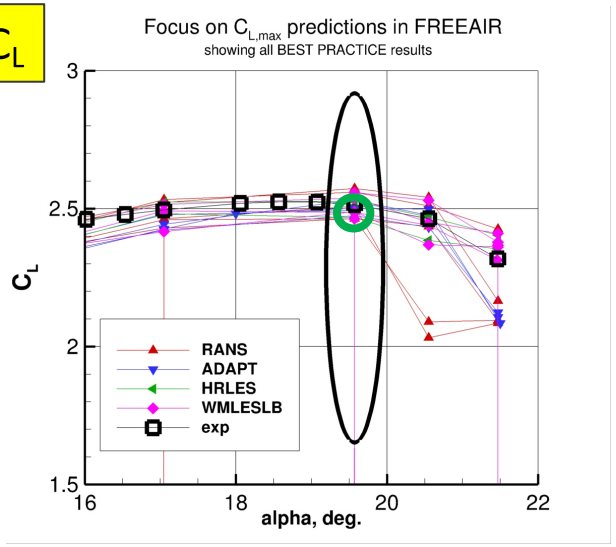


Reasonable outboard separation

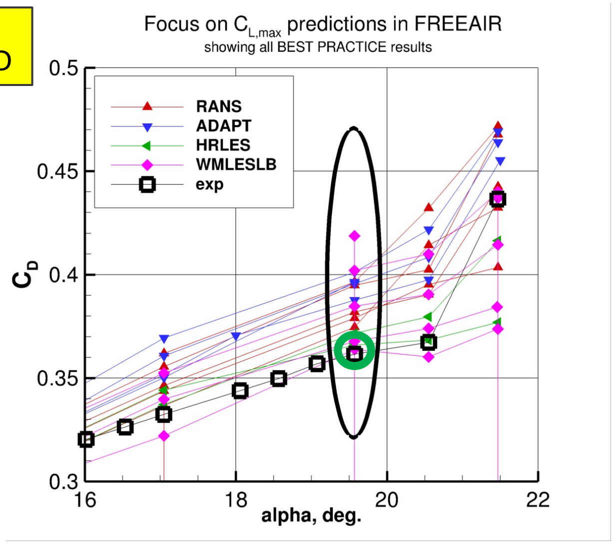


Test Case 2 – $C_{L,max}$ Study (free air)

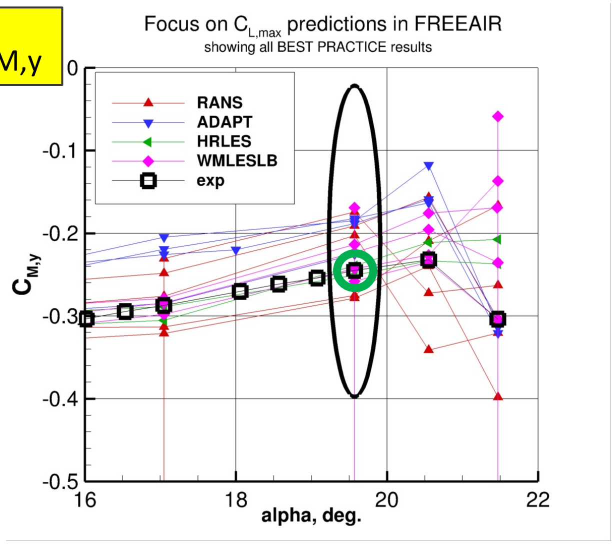
C_L



C_D



$C_{M,y}$



W-050.1

No pics provided

Test Case 2a – Summary

(looking at the results closest to $C_{L,exp}$ at corrected AoA=19.57 deg.)

- RANS results typically predicted too much outboard separation
  - Most results used SA model
  - All adapted RANS SA results also predicted too much outboard separation
  - SA exceptions: R-025.3 and R-037.3 (both same code on overset grids) on fixed RANS grids produced reasonable outboard separation (SA model)
    - But running on a finer overset grid yielded massive separation like others (see AIAA-2022-1554)
- HRLES and WMLES results typically predicted reasonable outboard separation
  - Similar, but not identical
  - Exception: W-047, which showed no outboard separation whatsoever

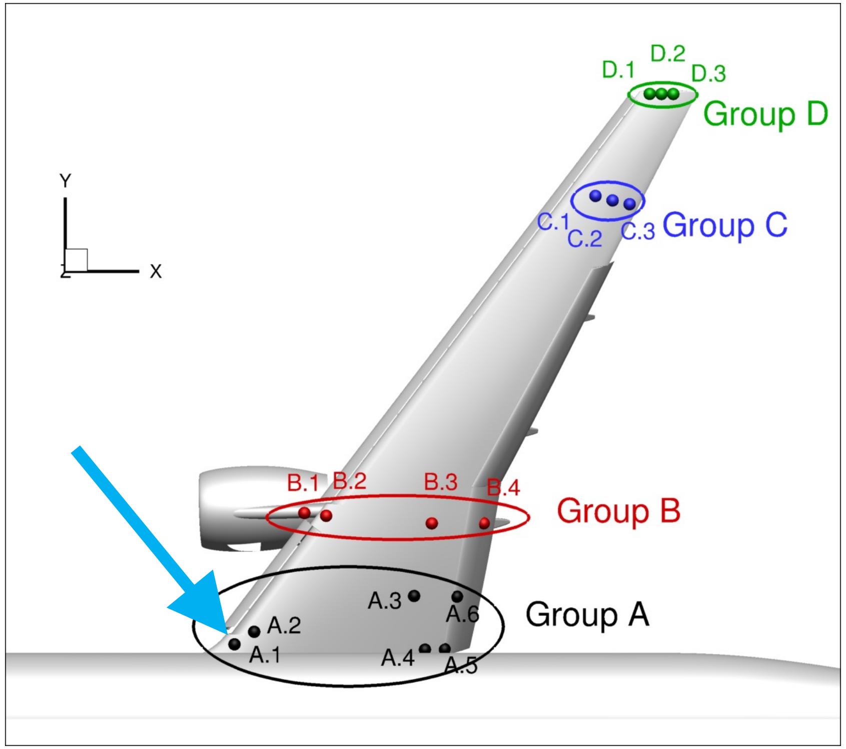
KQ#1, Velocity profile analysis

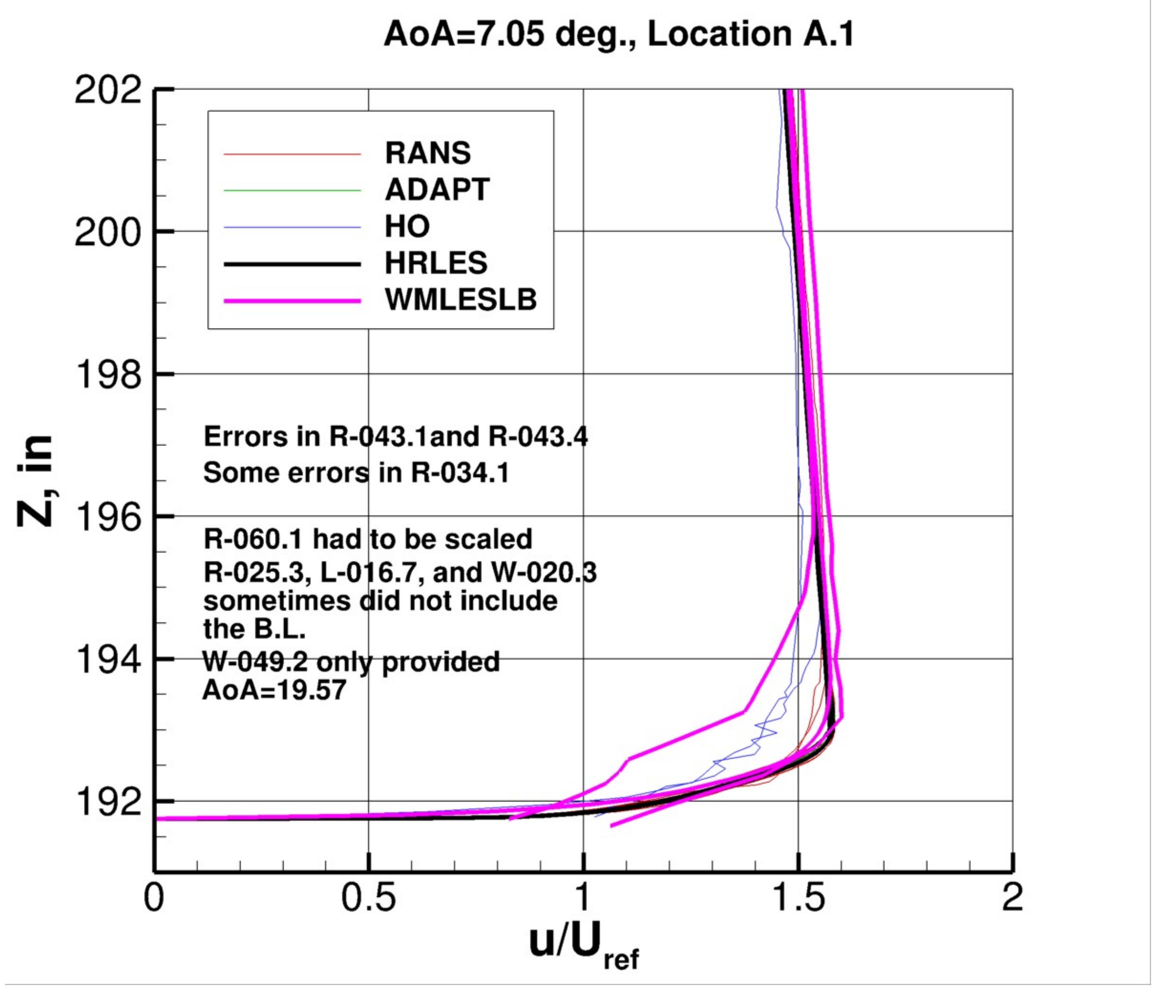
Velocity Profile Study

- Objective
  - Examine <u>consistency</u> of CFD velocity profile data
- Background
  - There are no corresponding experimental data
- Data Comparisons
  - Examine u profiles for AoA=7.05 and 19.57 deg.
  - Data taken from Case 2a in most cases
    - (Case 1 used for AoA=7.05 deg. if 2a not available)
  - RANS has the most data, HO the least
- Findings

AoA=7.05 deg.

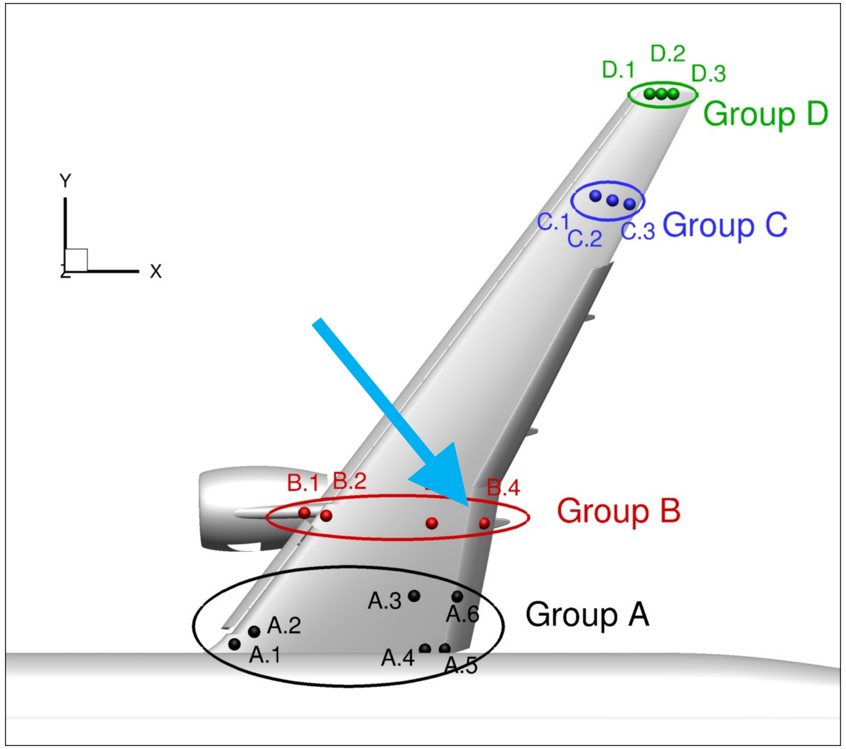
Looking for Trends in Velocity Profiles

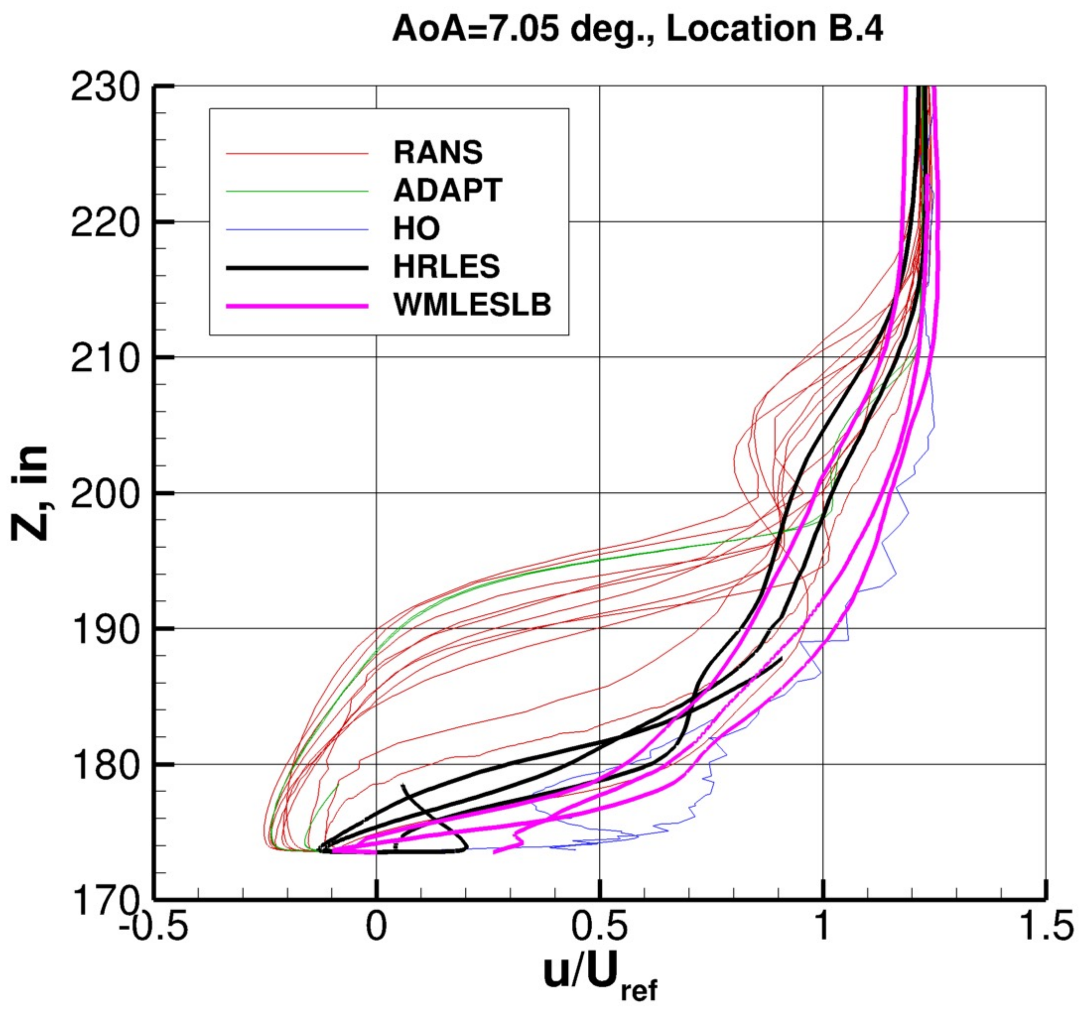




- Most CFD results are reasonably consistent
- Exceptions:
  - HO results
  - W-047

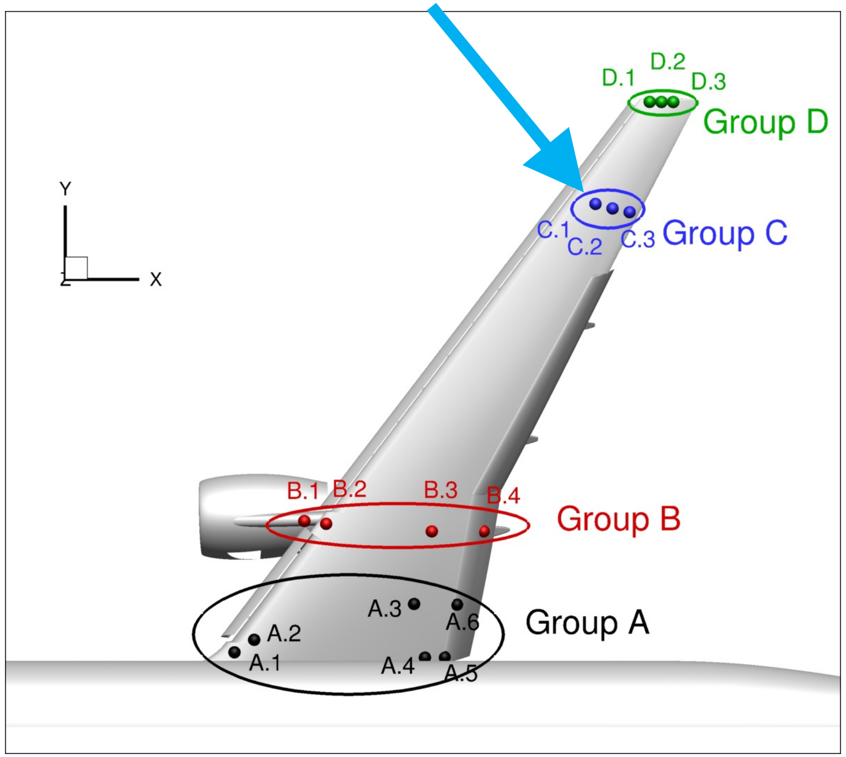
Looking for Trends in Velocity Profiles

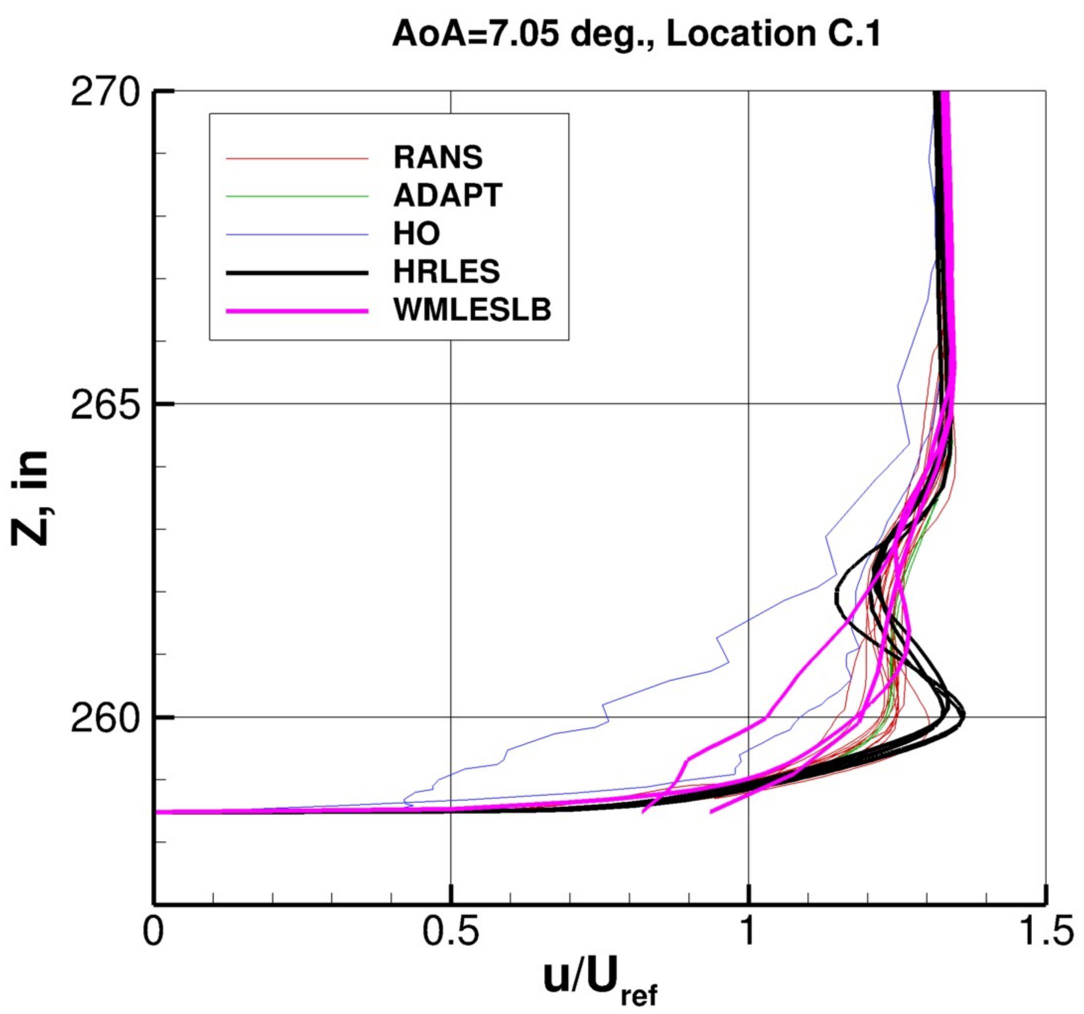




- No clear trends among RANS; all are separated
- HRLES and WMLESLB are less separated
- HO has “wiggles”
- L-005 has odd shape

Looking for Trends in Velocity Profiles

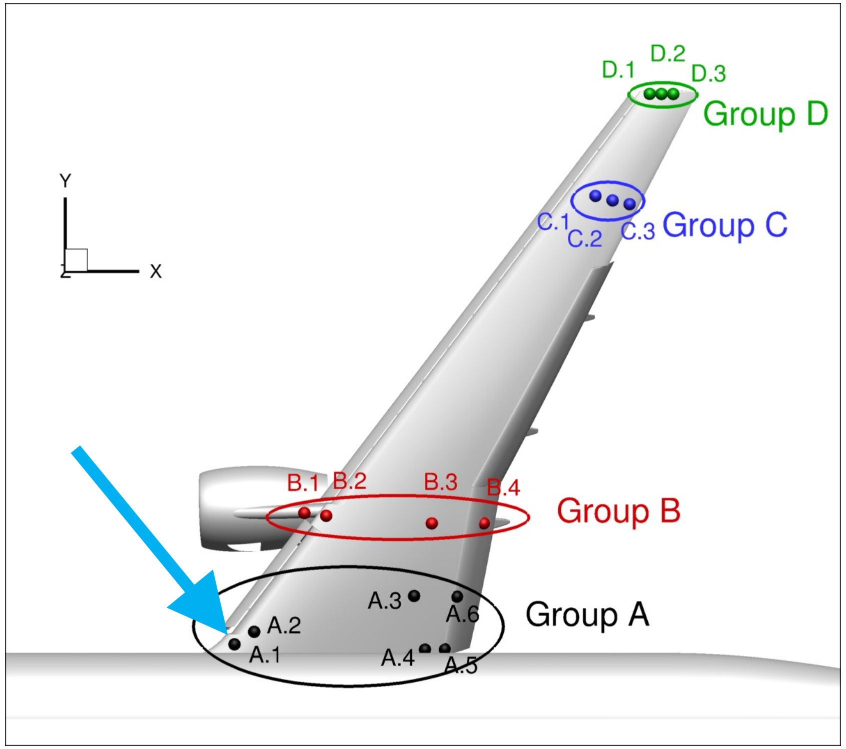


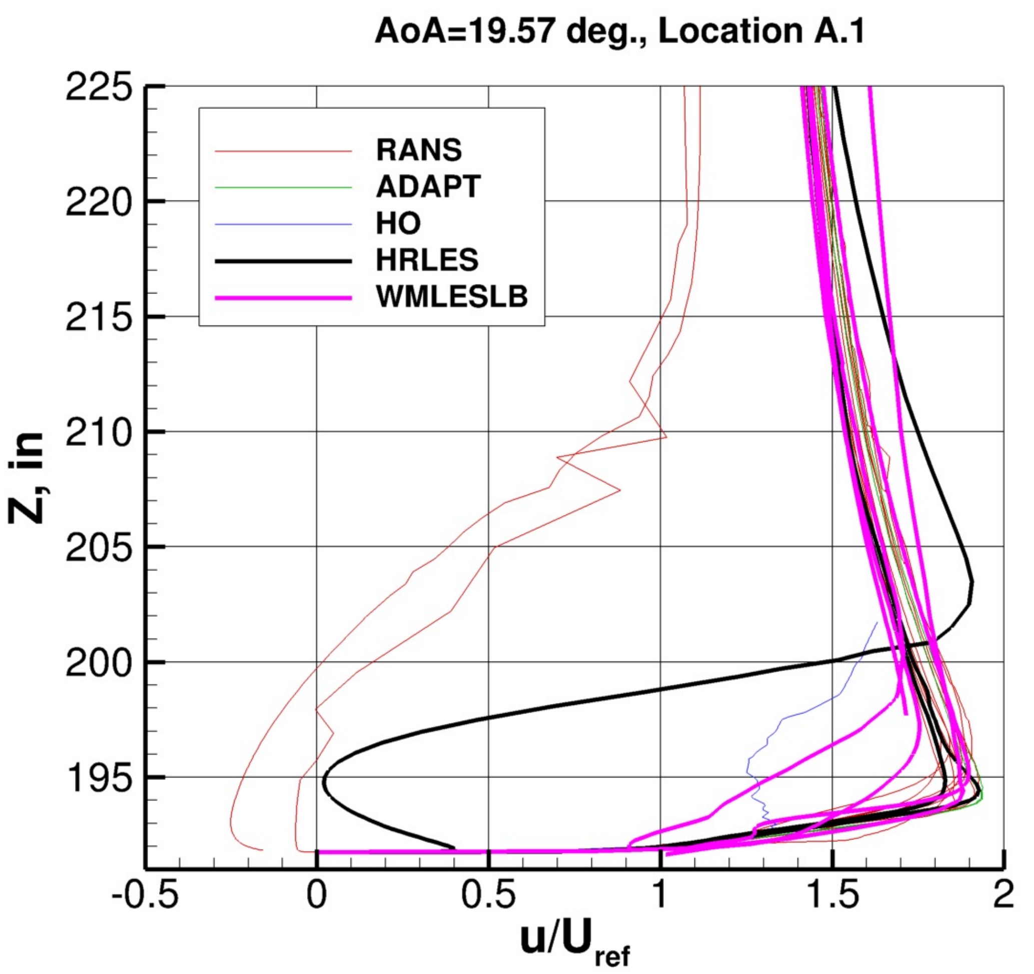


- Most RANS generally similar
- All HRLES generally similar
- WMLESLB generally similar except for W-047
- HO has “wiggles”; results are different

AoA=19.57 deg.

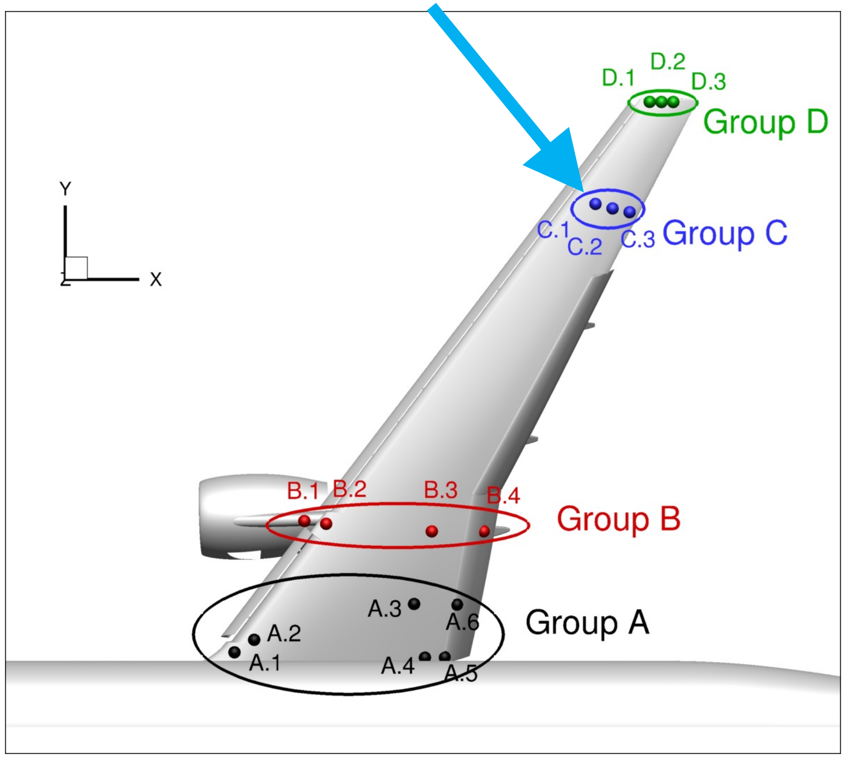
Looking for Trends in Velocity Profiles

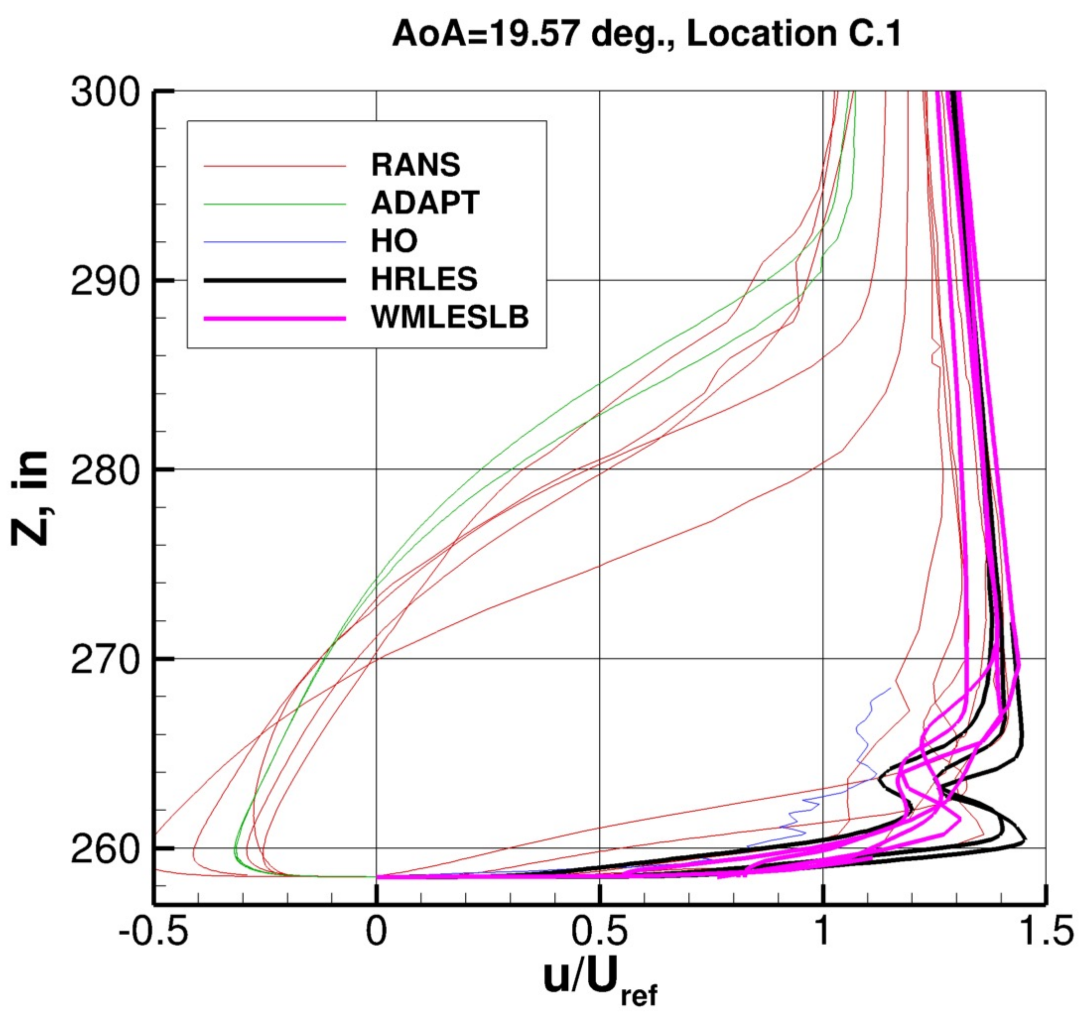




- Many CFD results are reasonably consistent
- Exceptions:
  - R-011.1, R-059.4, H-013.1, L-001.3, W-047
  - W-032 has slightly different farfield level

Looking for Trends in Velocity Profiles

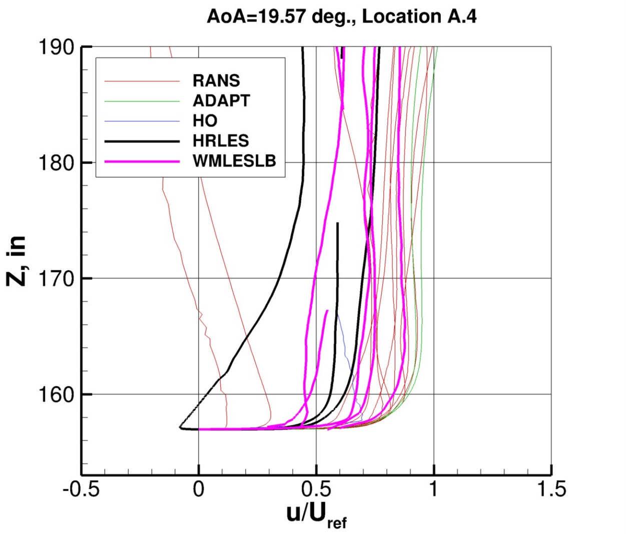


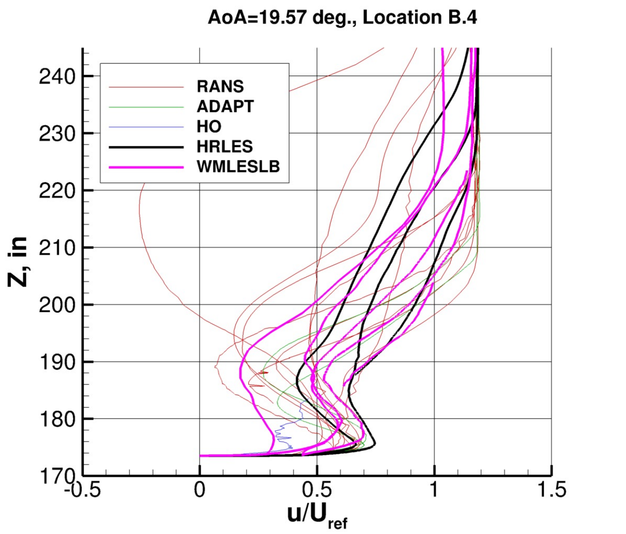


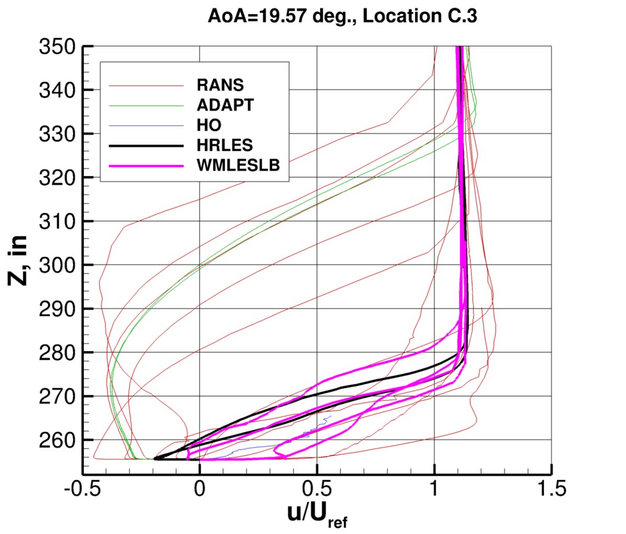
- Two trends: separated and attached
    - Significant variations within those trends
    - All scale-resolving results are attached

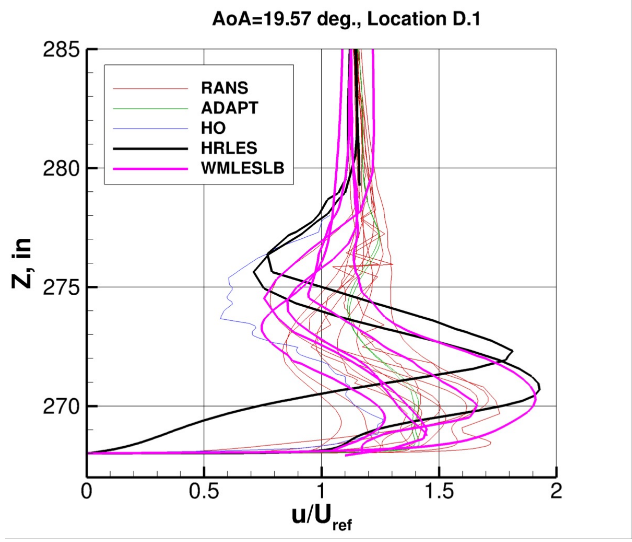
Looking for Trends in Velocity Profiles

- At all other locations, results for AoA=19.57 deg. do not seem to yield clear trends
  - Results are very diverse, even among scale-resolving results
  - Examples:









Velocity Profile Study – Summary

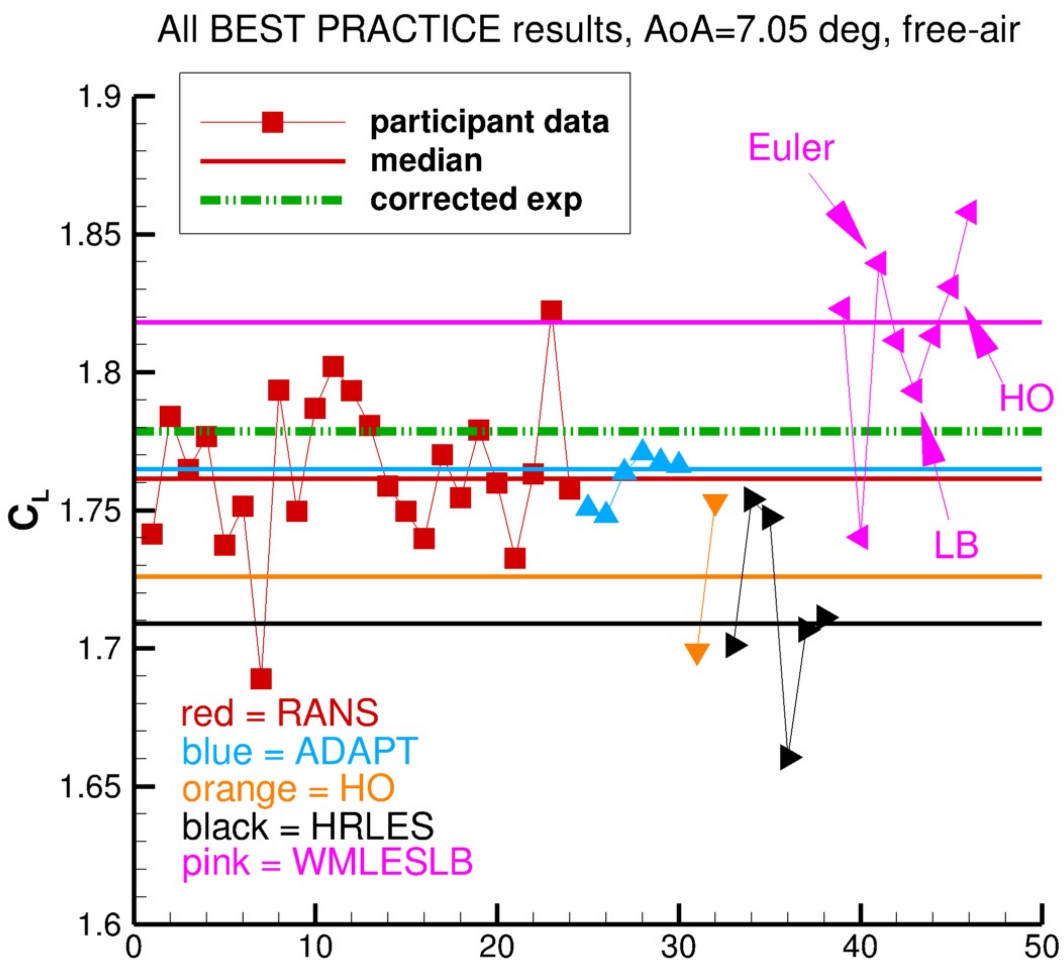
- AoA=7.05 deg:
  - HO profiles did not look realistic
  - RANS (including ADAPT) were somewhat consistent in some areas (A.1, A.4, A.5, A.6, B.1, and C.1), very diverse in others
  - HRLES results were particularly self-consistent at most of the outboard stations (C and D)
  - Both HRLES and WMLESLB tended to exhibit less separation at B.4, where RANS yielded large separation
- AoA=19.57 deg.:
  - Generally, profiles are “all over the map”
  - Near $C_{L,max}$, even though many of the scale-resolving simulations are predicting close-to-correct lift levels, the flowfield (u velocity) details between them are different

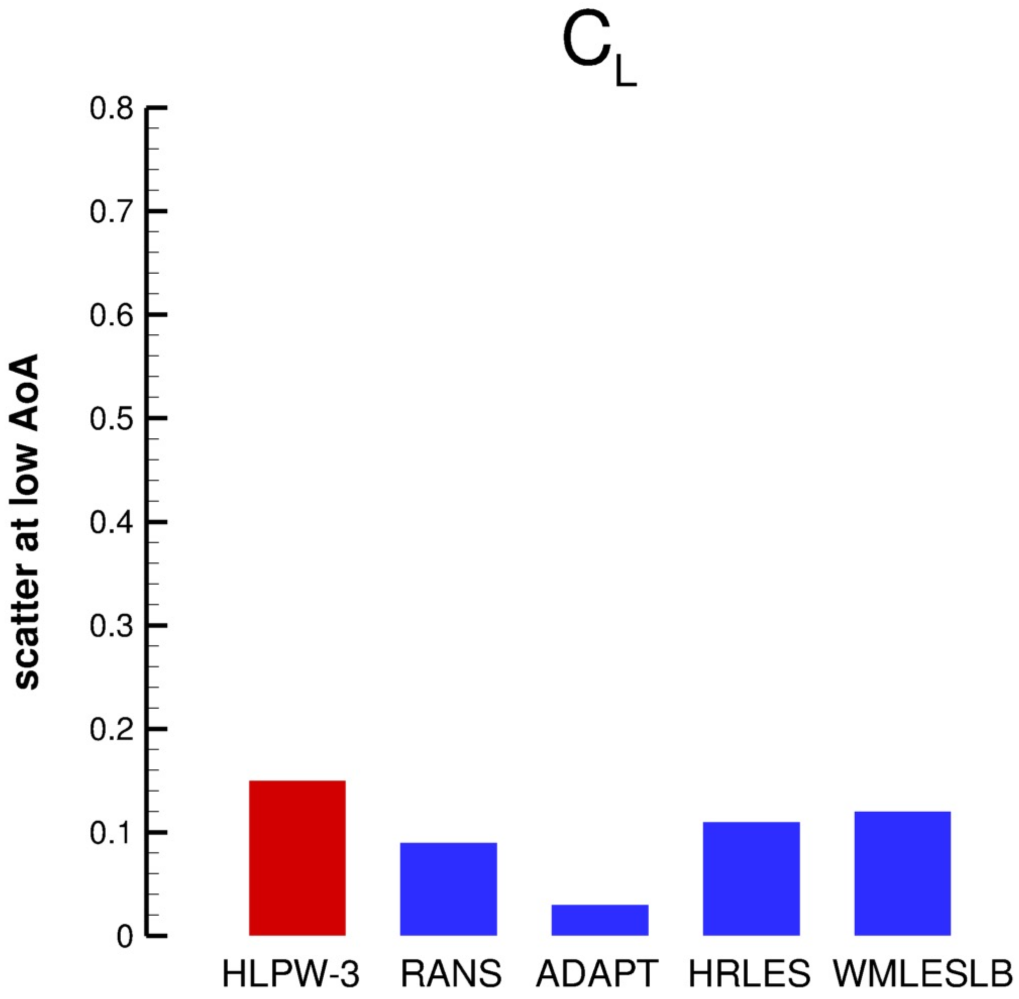
KQ#1, Statistical analysis

Statistical Analysis

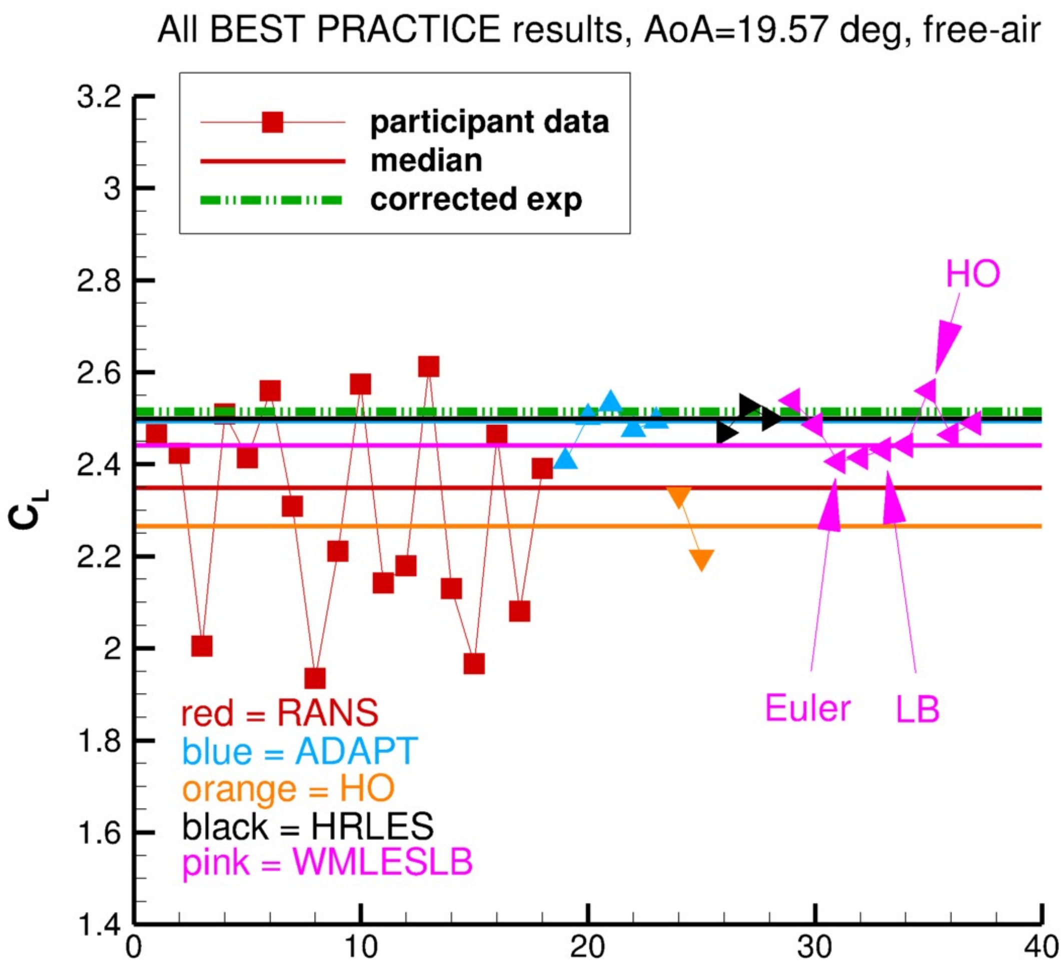
- **PURPOSE**: assess trends in medians and variation of results
- BEST PRACTICE participant data were used
  - Case 2a results were used at AoA=7.05^{o} (as representative of results in linear part of lift curve) and at AoA=19.57^{o} (as representative of near $C_{L,max}$ conditions)
  - A few Case 1a results were used for AoA= 7.05^{o} when Case 2a results not available
- Examine results divided by TFG (looking for trends)
  - RANS = RANS TFG
  - ADAPT = Adaptation TFG
  - HO = High Order TFG <- note: statistics were ignored because only 2 entries
  - HRLES = Hybrid RANS TFG <- note: only had 3 entries at 19.57 deg.
  - WMLESLB = WMLES and LB TFG
- Compare data scatter with that from HLPW-3
- Also assess the general trend in accuracy (compared with corrected experimental data)

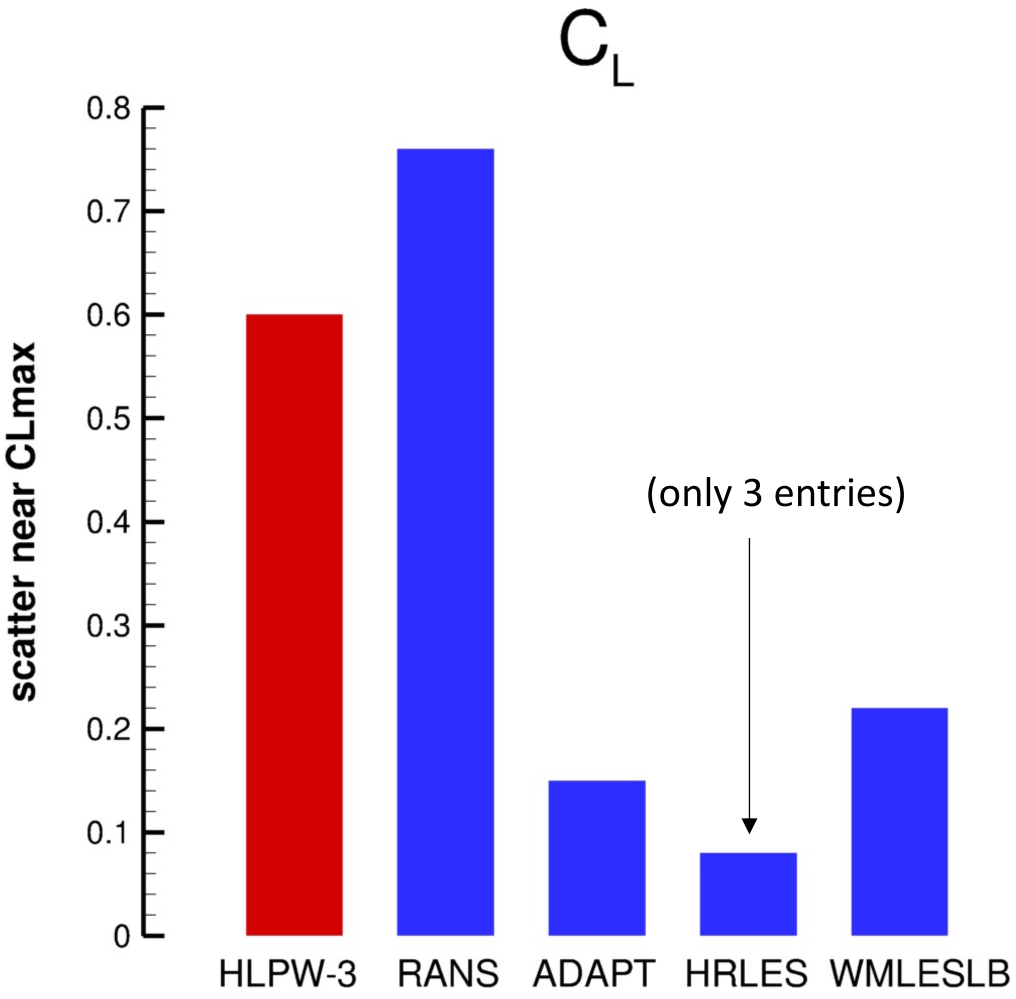
C_L: Results at AoA=7.05 deg



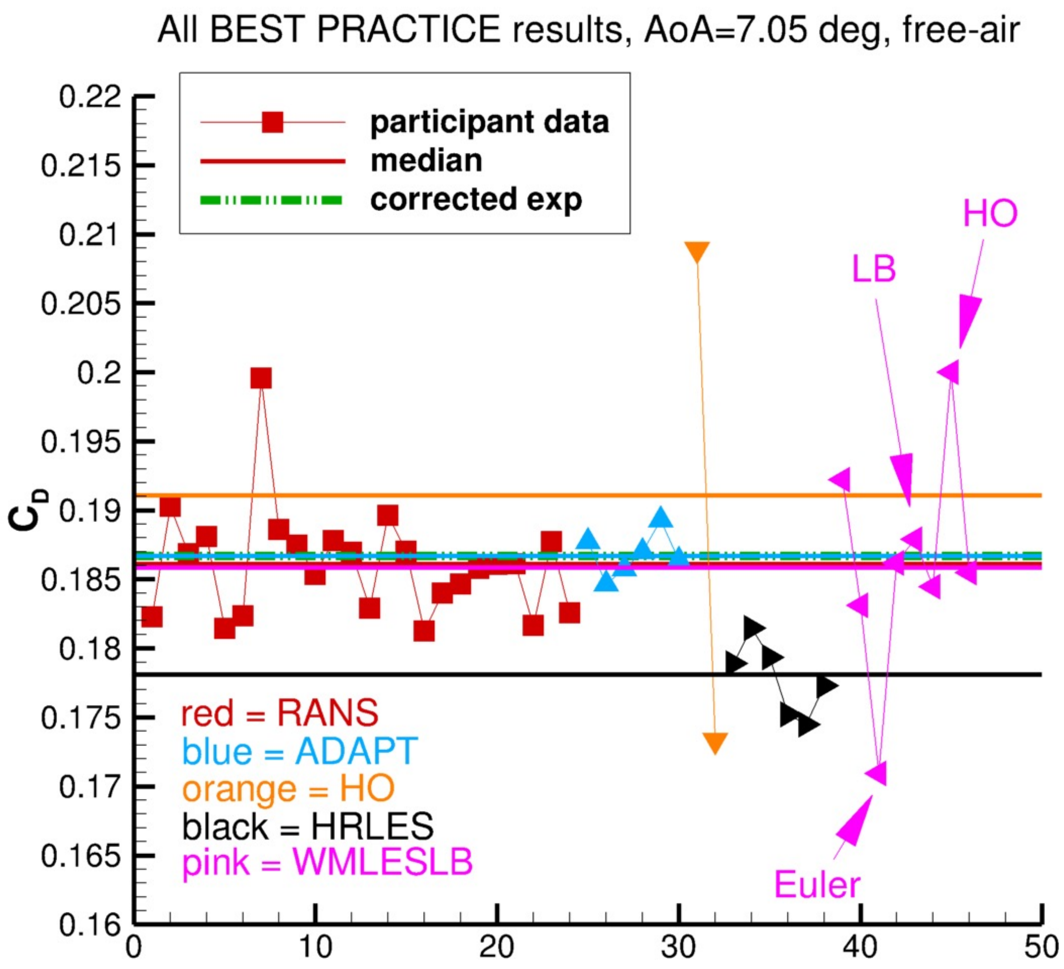


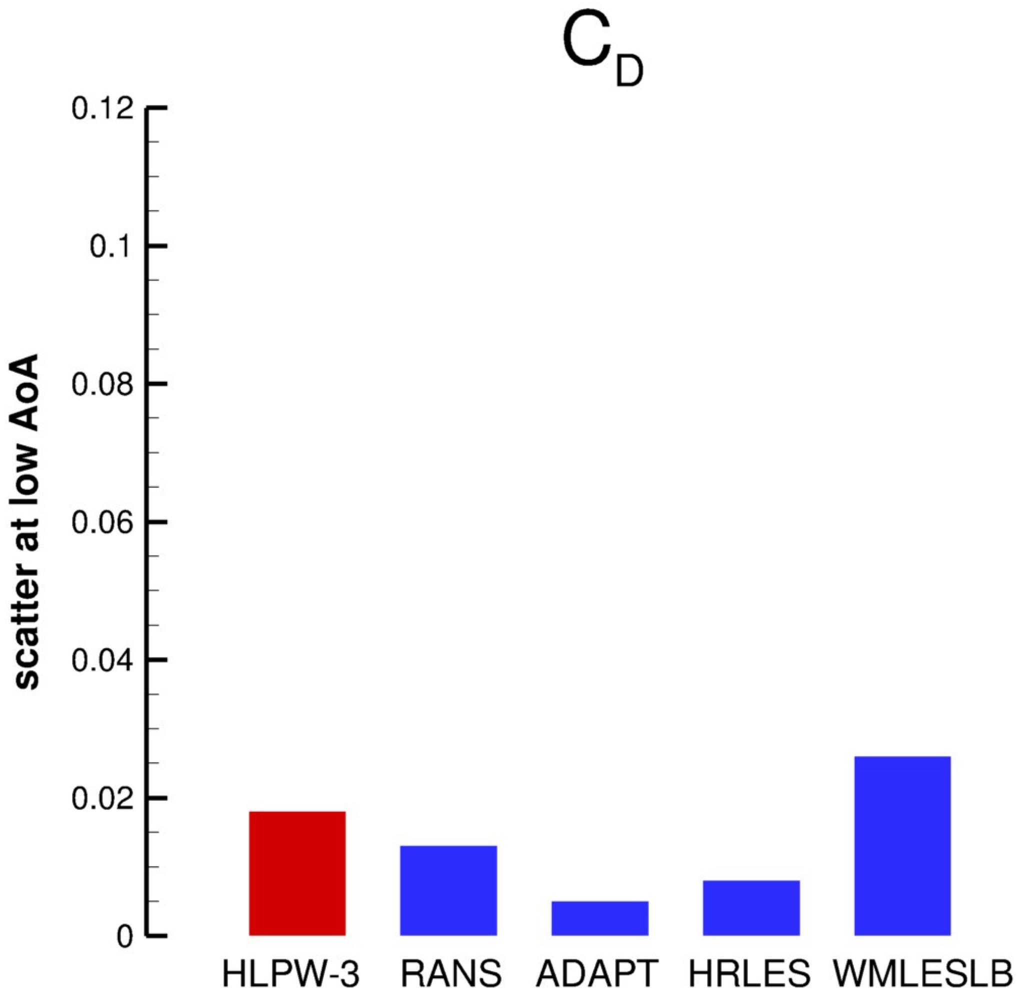
C_L: Results at AoA=19.57 deg



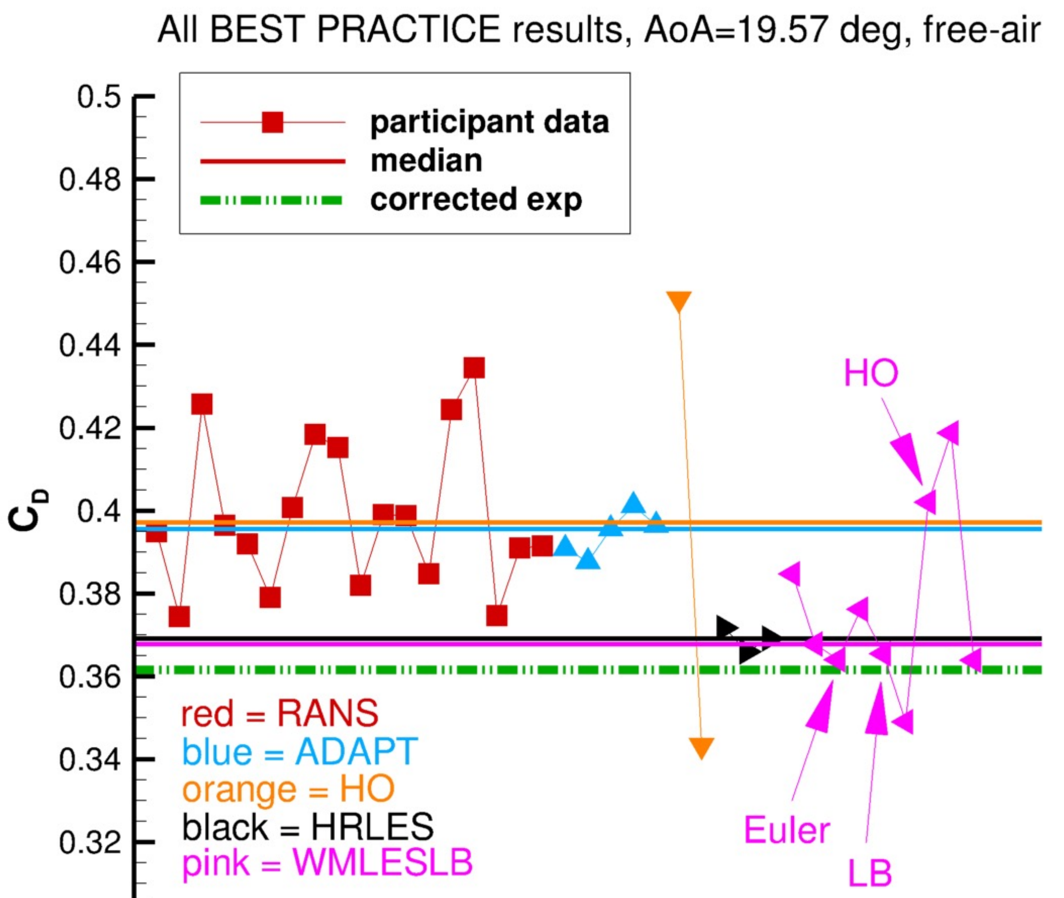


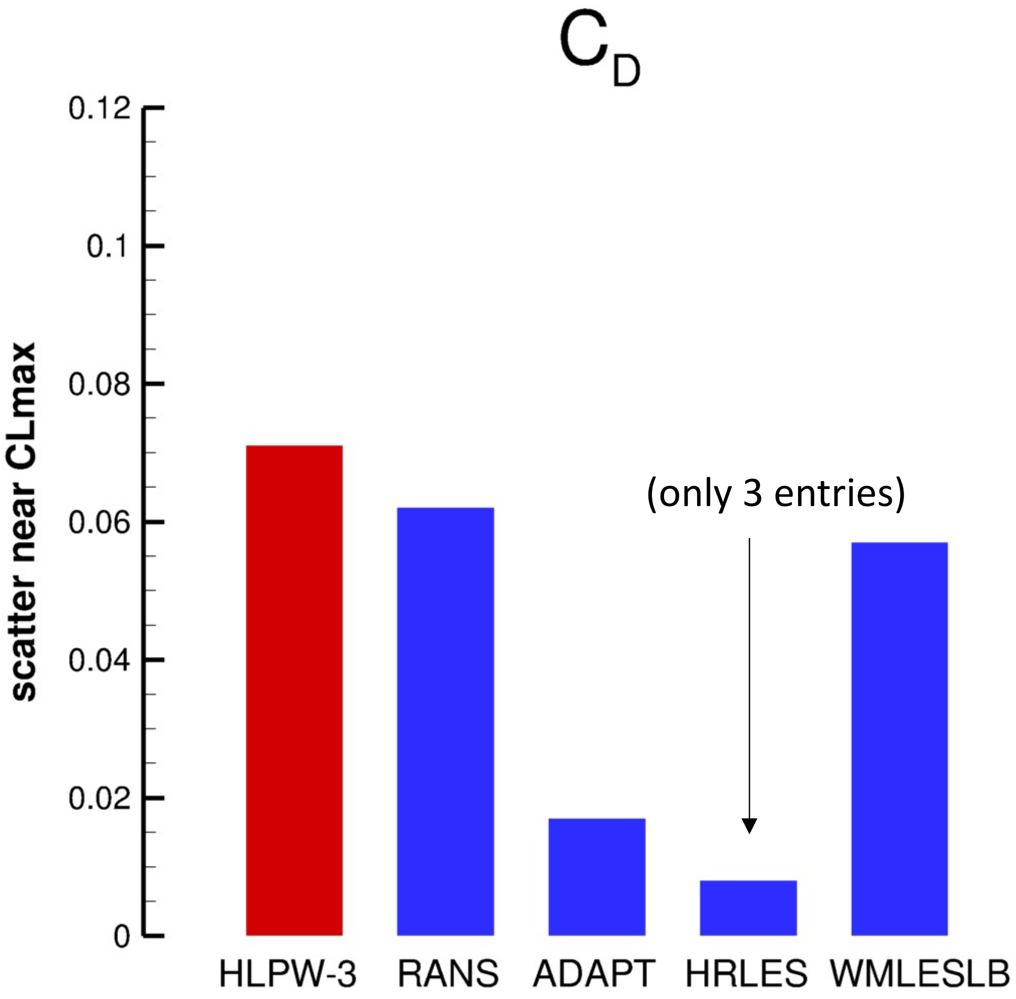
C_D: Results at AoA=7.05 deg



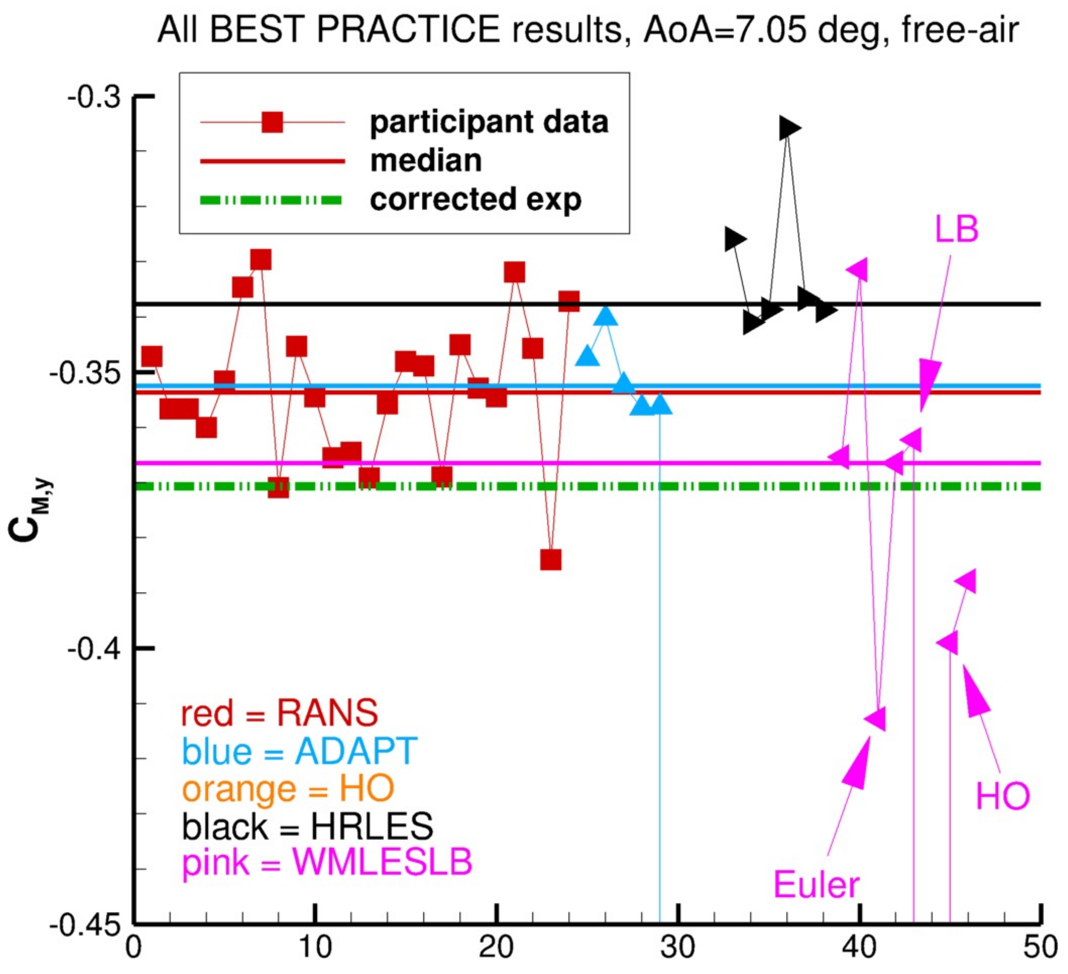


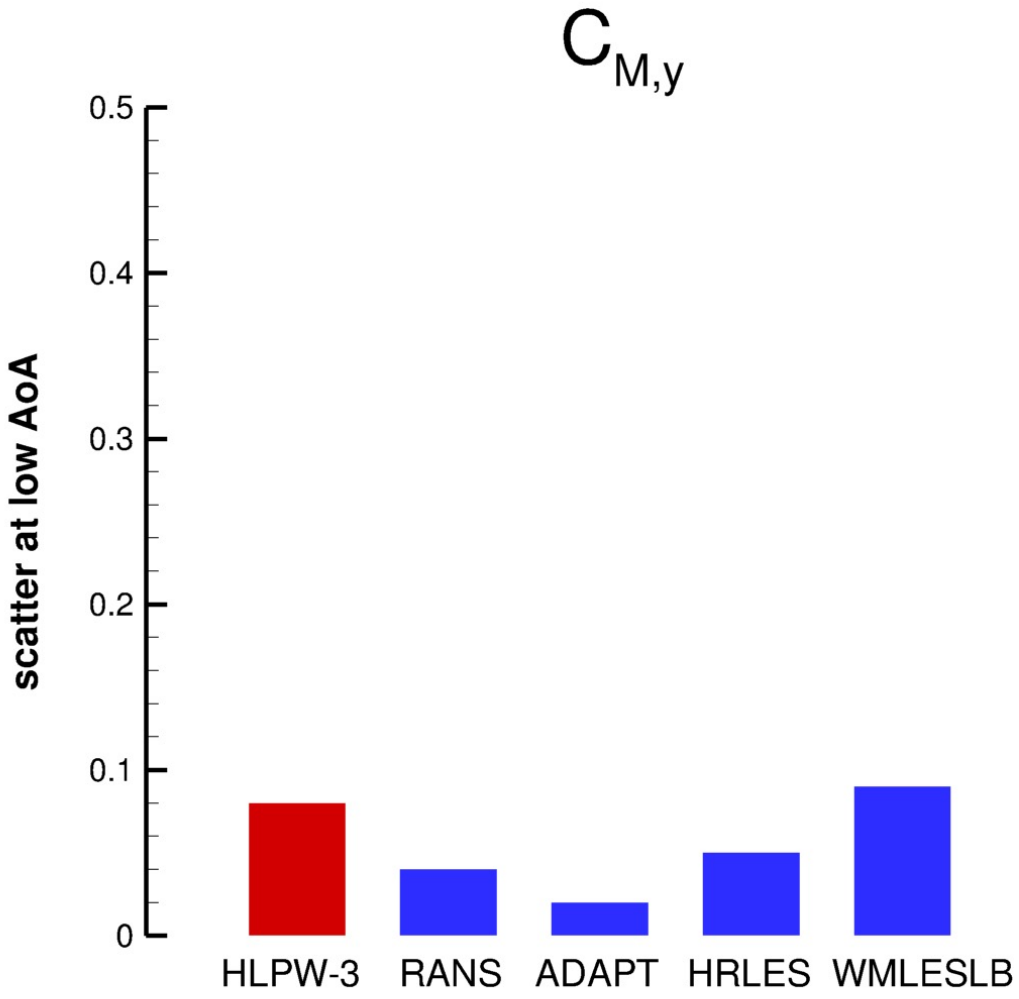
C_D: Results at AoA=19.57 deg



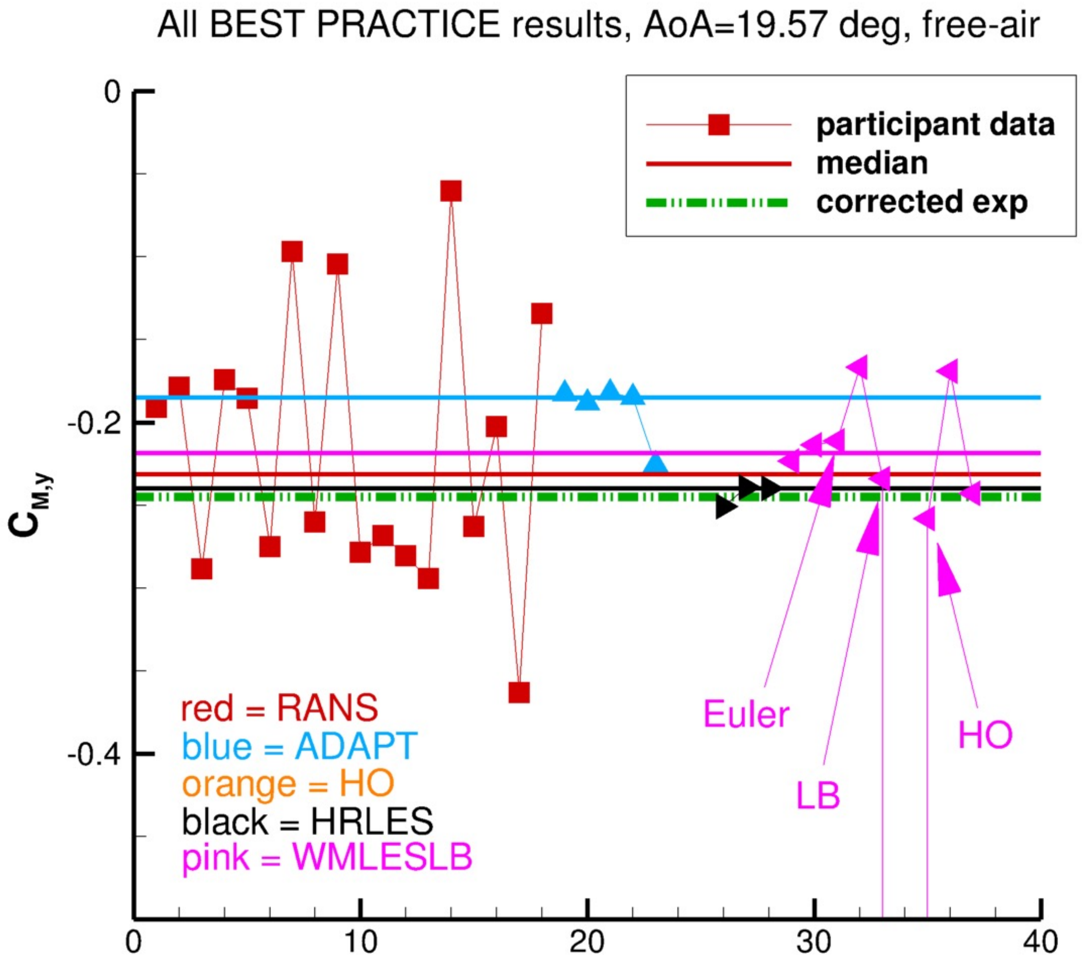


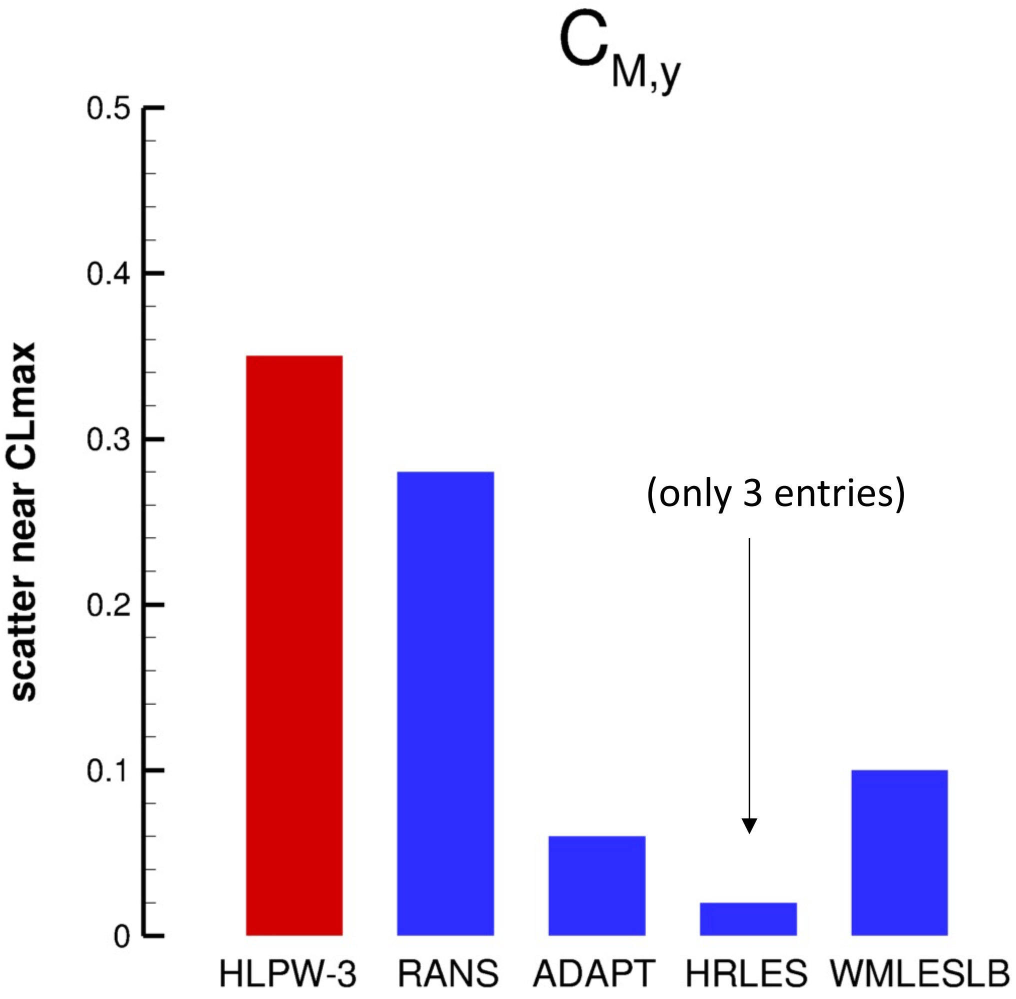
$C_{M,y}$: Results at AoA=7.05 deg





$C_{M,y}$: Results at AoA=19.57 deg





Statistical Analysis Summary: Scatter

- At AoA=7.05 deg. (linear part of lift curve)
  - ADAPT (which was RANS) always had the lowest scatter level
  - RANS scatter level was notably lower than from HLPW-3 ($^1/_2$ to $^3/_4$ as high)
  - HRLES and WMLESLB C_L scatter levels were similar to RANS
- At AoA=19.57 deg. (near $C_{L,max}$)
  - ADAPT always had the lowest scatter levels (HRLES was also very low, but only had 3 entries)
  - RANS C_L scatter level (near 0.75) was higher by about 25% than that from HLPW-3 (C_D and $C_{M,y}$ scatter levels were a bit lower)
  - WMLESLB C_L scatter level was significantly lower than for RANS

Statistical Analysis Summary: Accuracy

- At AoA=7.05 deg. (linear part of lift curve)
  - RANS and ADAPT medians were closest to the measured C_L data (within $\Delta C_L = 0.02$)
  - HRLES tended to predict C_L too low (by about $\Delta C_L = 0.07$)
  - WMLESLB tended to predict C_L too high (by about $\Delta C_L = 0.04$)
- At AoA=19.57 deg. (near $C_{L,max}$)
  - RANS median tended to be low compared to the measured C_L data (by $\Delta C_L = 0.17$)
  - ADAPT, HRLES, and WMLESLB were closest to the measured C_L data (within $\Delta C_L = 0.07$)
    - But ADAPT's median $C_{M,y}$ and C_D are further away from measured data than HRLES and WMLESLB, and Case 2a results indicated massive outboard separation for ADAPT (evidence of possible error cancellation: right C_L for wrong reasons)

Summary of all KQs

KQ #1 – What CFD solution methodology(ies) currently provides the best/most-consistent approach to predicting (a) increments due to flap deflection, and (b) maximum lift?

- For predicting increments due to flap deflection (involving separated flow), no method is best, no method is consistent
  - Need more studies from scale-resolving methods to determine their capability (limited results from LB indicate favorable trend)
- For predicting maximum lift, HRLES and WMLESLB are far more accurate than RANS (right answer for right reasons), but consistency is still lacking

KQ #2 – What are important lessons learned in high-lift CFD analysis explored in HLPW-4? (primarily extracted from the TFG talks)

- RANS: D-level meshes (200+M nodes) appear to be “sufficient” in the linear range away from stall
- RANS: No conclusions about mesh suitability near stall
- RANS: As currently deployed in practice, fixed-grid RANS cannot accurately predict aerodynamic behavior near stall, nor predict deltas due to flap angle changes well away from stall
- ADAPT: Regions of suspected multiple solutions are made more consistent with mesh refinement and better iterative convergence
- ADAPT: Automated mesh adaption can track/resolve vortices & wakes
- HO: Best-practice meshing guidelines for HO are different than standard low-order RANS
- HO: On a given Q2 mesh, P2 accuracy demonstrated much improved resolution compared to P1
- HRLES: Consistent improvement over RANS near and beyond $C_{L,max}$ (less outboard separation)
- HRLES: Grid design that leads to RANS mesh convergence does not lead to HRLES mesh convergence
- HRLES: Typically 10-15x increase in core hours compared to RANS
- HRLES Best Practice:
  - Both cold-start and warm start (rotating from prior AoA) superior to restart-from-RANS
  - HRLES: 40 CTUs typically sufficient averaging time
- HRLES: For half-model testing, matching tunnel boundary layer shape & thickness remains a challenge; it has an impact on the physics of the solution
- HRLES & WMLES: Increased mesh resolution in separated regions helps; too coarse -> larger (nonphysical) separations
- WMLESLB: Large sensitivity to mesh resolution at and beyond stall; mesh can have big impact (isotropic vs. anisotropic cells, etc.)
- WMLESLB: For half-model testing, further investigations are needed to understand competing roles of tunnel BL, standoff-height, and tunnel blockage
- WMLESLB: Typically 5-10x increase in core hours compared to RANS
- WMLESLB Best Practice:
  - Numerical tripping is more cost-effective than exact representation of physical tripping
  - High AoA cases require longer run times to make sure flow patterns do not change and stationarity is achieved

KQ #3 – What geometry and meshing best practices are appropriate for high-lift CFD analysis for RANS, Wall Modeled LES, and Hybrid RANS/LES simulations?

- Data Sources*
  - Geometry and Mesh Preparation TFG Challenges
    - Build up the nominal CRM-HL from constituent component geometry files
    - Create CRM-HL geometry files with deflected flaps
    - Create surface mesh suitable for purpose on CRM-HL and identify geometry-related meshing issues
    - Use 3D scan data of physical model in CFD mesh generation workflow and identify issues
  - Participant Questionnaire (PQ) responses from across all TFGs
    - Information provided by participants who created their own meshes regarding geometry and meshing processes, performance, and issues
  - TFG Leader Summary Presentations
    - Participant Data
    - Key Findings & Lessons Learned

* KQ summary based on initial review and observations – further analysis needed/planned

KQ #3 – What geometry and meshing best practices are appropriate for high-lift CFD analysis for RANS, Wall Modeled LES, and Hybrid RANS/LES simulations?

Disclaimer*: Limited participation in geometry and meshing challenges make it difficult to draw concrete conclusions on best practices. Observations for KQ#3 require further exploration.*

- Tangential connections in geometry (like WUSS/Wing) should be trimmed in a consistent manner prior to meshing.
  - Further work required to determine trim location that represents model appropriately and reduces modifications necessary to mesh according to simulation needs.
- CFD analysts prefer topological mark-ups (splits) to be pre-defined by CAD designer to reduce manual efforts.
  - Topological mark-ups necessary for current tools to provide mesh alignment and sizing in addition to some post-processing operations.

KQ #3 – What geometry and meshing best practices are appropriate for high-lift CFD analysis for RANS, Wall Modeled LES, and Hybrid RANS/LES simulations?

- Solid model/body geometry or parametric representations may be preferred over piecemeal surface representations to enable easier geometry assembly and modification.
- In the context of this workshop, using surrogate/virtual geometries may provide greater success with adaptive and high order meshing.
  - Alternatively, use CAD with geometry boundary representation tolerances less than the smallest expected surface mesh edge length refinement (if available).
- Current best metrics for evaluation of High Order mesh validity and quality are:
  - Jacobians, Scaled Jacobians
  - Shape distortion metrics like shape conformity provide quantitative measure of the error between the curved mesh and the geometry shape.

KQ #3 – What geometry and meshing best practices are appropriate for high-lift CFD analysis for RANS, Wall Modeled LES, and Hybrid RANS/LES simulations?

- Use preliminary simulations to identify regions that would benefit from point clustering (i.e., regions of high gradient) on the surface and the volume domain. Redistribute or add points to add resolution in these regions.
- As mesh family refinement levels are created, check associativity between the surface mesh and the database to ensure that all points remain on the underlying database. Perform projection operations to resolve any unassociated points.

KQ #4 – What roadblocks in geometry preparation and mesh generation for CFD prevent analysts from creating geometry/meshes suitable for high-lift aerodynamics simulations in a turn-key, rapid manner?

- Data Sources*
  - Geometry and Mesh Preparation TFG Challenges
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* KQ summary based on initial review and observations – further analysis needed/planned

KQ #4 – What roadblocks in geometry preparation and mesh generation for CFD prevent analysts from creating geometry/meshes suitable for high-lift aerodynamics simulations in a turn-key, rapid manner?

- Lack clear understanding of how geometry prep choices impact meshing and simulations in complex geometric regions.
  - Pinch points (WUSS/Wing)
  - Bracket junctions with wings, flaps, slats
  - Mesh resolution and alignment in gaps
  - Outboard wing separation

Clearer understanding can inform development of geometry prep best practices.

- Lack consistent best practices for build-up of complex geometric regions that require special handling for meshing.
  - Tangential connections (WUSS/Wing, FSF/Wing)
  - Degenerate NURB Construction and Handling
  - Inboard/Outboard Flap Partial Gap Fill
  - Narrow slat bracket gaps
  - Definition and transformation of geometry components
  - Topological splits (Wing, Slats, Flaps, Nacelle)

Primary drivers of manual intervention in geometry prep and meshing processes

KQ #4 – What roadblocks in geometry preparation and mesh generation for CFD prevent analysts from creating geometry/meshes suitable for high-lift aerodynamics simulations in a turn-key, rapid manner?

- Lack access to, or sufficient time on, computational resources large enough to broadly explore mesh resolution for grid-convergence studies.
  - Few participants have access to resources that enable them to run large meshes/simulations
  - Participants with access to large enough computational resources do not have enough allocated time on resource to perform extensive studies.
- Large file exchange continues to be problematic and cumbersome.
- Computational costs still pose a substantial hurdle to using methods other than RANS quickly and efficiently.
  - Further investigations needed to understand what strategies can be employed to reduce computational costs for these methods.

KQ #4 – What roadblocks in geometry preparation and mesh generation for CFD prevent analysts from creating geometry/meshes suitable for high-lift aerodynamics simulations in a turn-key, rapid manner?

- Clear understanding of the differences in requirements for meshing for RANS, Hybrid RANS/LES, WMLES/LB, High Order, and Adaptive simulations in different regions of the lift curve.
  - Targeted grid refinement in separated-flow regions provide significantly improved HRLES and WMLES predictions
  - Understanding impact of mesh type in the near-body and off-body regions on simulation accuracy for WMLES
  - Understanding levels of mesh refinement and iterative convergence necessary to resolve instances (if possible) of multiple solutions in adaptive meshing.
  - Further work needed in identification of mesh quality metrics and ideal thresholds for RANS, HRLES, WMLES, and HO.
    - How do we quantify what a “best practice” mesh is for RANS, HRLES, WMLES, and HO?

KQ #5 – What was the impact/effectiveness of the existing test data collected for the CRM-HL configuration in understanding high-lift flow physics? If not effective, what is needed?

- What proved to be (at least partially) effective:
  - **Corroborating data sources** for geometric configurations and flow conditions used for primary test cases (F/M + surface pressures + mini-tufts + oil flow) – generally better than what existed for previous workshops, and (generally) provided ability to determine if a simulation got the "right answer for the right reasons".
  - Definition of the **WT contraction and diffuser sections**, and **updated test section geometry**, along with appropriate **run procedures** to use to mimic Q5m test data acquisition, provided valuable insights (and more questions!) – never available in previous workshops.
- What proved to be problematic:
  - Not knowing **full characterization of tunnel onset conditions and wall/floor boundary layer development** hampered efforts to fully understand differences seen between test data and in-tunnel CFD simulations, particularly at $C_{L,max}$.
  - **Lack of off-body flow field** data hampered efforts to understand details of the stall mechanism at $C_{L,max}$, particularly near and downstream of the nacelle/pylon intersection with the wing – requested streamwise vorticity cuts hinted at where data collection would be effective in the future.
  - **Detailed boundary layer profiles** at key locations (pressure gradients, SOB, BL confluence, etc.) are needed to help assess and train CFD all simulations technologies, particularly wall-models.

KQ #6 – What are the significant remaining technical areas that require additional focus in future workshops? (answers from questionnaire)

CFD Technology

- Meshing Technology
  - Mesh resolution rules, mesh convergence/independence, and the mesh fidelity needed near $C_{L,max}$
  - Focus on mesh generation with even more complexity; more relevance to industry
  - High order and curved meshes
- Adaptive Meshing Technology
  - Grid adaption for eddy-resolving methods
  - Euler+adaptive error control
- Flow Solver Technology
  - More focus on verification, reproducibility, and consistency
  - Hysteresis and solution path dependency
  - Turbulence model studies; wall function studies
  - Impact of different algorithms
  - Fidelity vs. cost
- Best practice guidelines

Test Cases

- Study configs with double or triple slotted flaps
- Unit validation problems that can be used by both RANS and hybrid

Characterization/Modeling of Experimental Set-Up

- Correct boundary conditions for physical validation data

Experimental Data

- More off-body (flowfield) wind tunnel data
- Better characterization of BLs (model and tunnel)
- Transition
- Cps closer to the wing-body juncture

Overall Summary

- Geometry preparation and fixed-grid meshing for high-lift flows is still difficult
  - How best to handle complex regions/junctions/pinch points
  - It is difficult to prescribe fixed-grid guidelines for different methodologies/codes/parts of lift curve
  - There are still practical size limitations (computing resources too limited for running)
- RANS is still problematic for predicting $C_{L,max}$ (separated flow)
  - Sometimes can get reasonable results (C_L) for the wrong reasons
  - Adapted mesh technology brings more consistency to the high-lift results
  - High-order is still an emerging technology for complex geometries like this
- Scale-resolving methods appear promising for predicting $C_{L,max}$
  - More work needed to establish best practice guidelines, achieve more consistency
- Additional measured data are needed to help validate CFD
  - Off-body boundary layer and vortex-structure data
  - Better wind-tunnel characterization
  - Influence of semi-span testing on $C_{L,max}$ characteristics (esp. inboard flowfield)

Acknowledgements

Thank you to the **AIAA,** the **Applied Aerodynamics TC,** and the **Meshing, Visualization, and Computational Environments TC** for their sponsorship and support.

Thank you to the **volunteers** and organizations that contributed many hours of their effort and/or resources over the last two years.

Next Steps

- If your CRM-HL meshes are not already posted to the HLPW website, please provide them to us ASAP
- Updates and corrections to submitted data will be accepted until February 11, 2022
- A virtual (zoom) post-workshop discussion session is planned
    - To ensure all have had an opportunity to digest/discuss the workshop results
    - Time/date to be announced (TBA)
- There will be HLPW/GMGW special sessions at AIAA Aviation 2022 in Chicago
    - Already populated based on participants who responded in the Fall
    - These include summary papers from each TFG and a global summary paper
- There are additional HLPW and/or GMGW workshops planned in coming years, dates TBA, using data to be collected in upcoming tests using multiple CRM-HL models

Seed Questions for Open Discussion

- What are the significant remaining technical areas that require additional focus in future workshops?
- Is there any hope for RANS being able to predict $C_{L,max}$ for the right reasons?
  - Should future HLPWs still include RANS submissions? (Is there more to learn?)
- What can/should we do to improve geometry handling for complex configurations?
- How can adaptive meshing and high-order methodologies be brought to the mainstream?
- What other meshing strategies should be pursued toward achieving grid-converged results for high-lift flowfields on complex geometries?
- What are next steps for scale-resolving methods applied to predicting high-lift flows?

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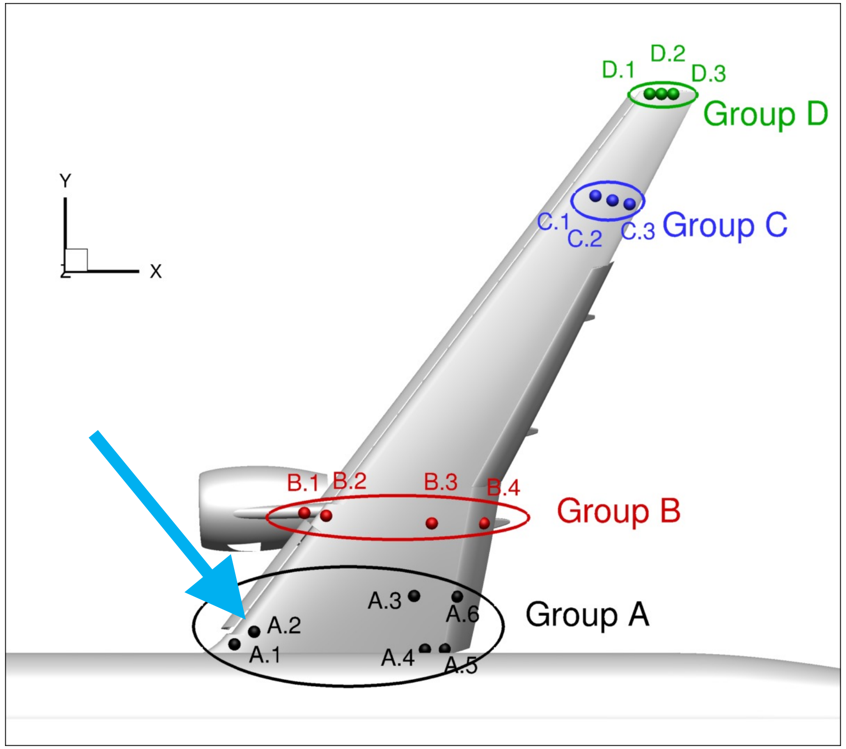
Backup Slides

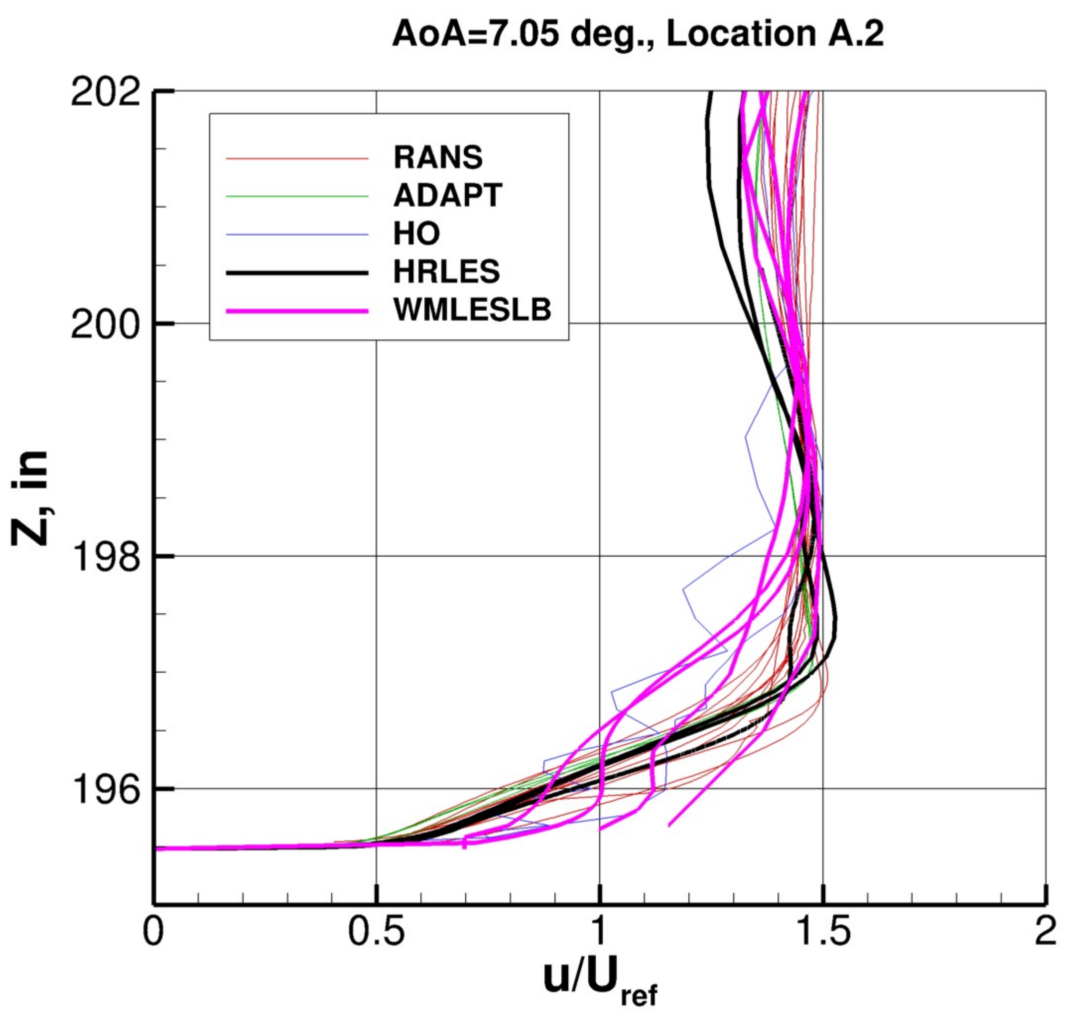
Comments on Test Cases – Summer Progress Meeting

- ✓ The 7.05 deg case is ”tough” for CFD (especially grid convergence) because of the separation. But capturing trends for this case is very important.
- ✓ When analyzing the data, have a filter on all of the datasets to establish which ones are truly a participants “best practice” instead of coarse grids, one-off things that didn't work so well.
- ✓ It would be useful to have some high priority AoAs (e.g., 7.05, 19.57) for Case 2a.
- ✓ Maybe it would be beneficial for different groups to run the same A/B tests, e.g., cold vs. warms start.
- It would be nice to have just one model configuration (beside the verification case) per TFG. Participants would then be able to focus their resources towards obtaining high quality solutions and more time to analyze the data. More time would be available for generating full polars, grid convergence studies and hysteresis studies.
- Do not have a single required grid. While the Committee grids work well for some solvers, they do not work well at all for others. We don’t know why.

✓ **Attempted to address in GMGW-3/HLPW-4 Workshop**

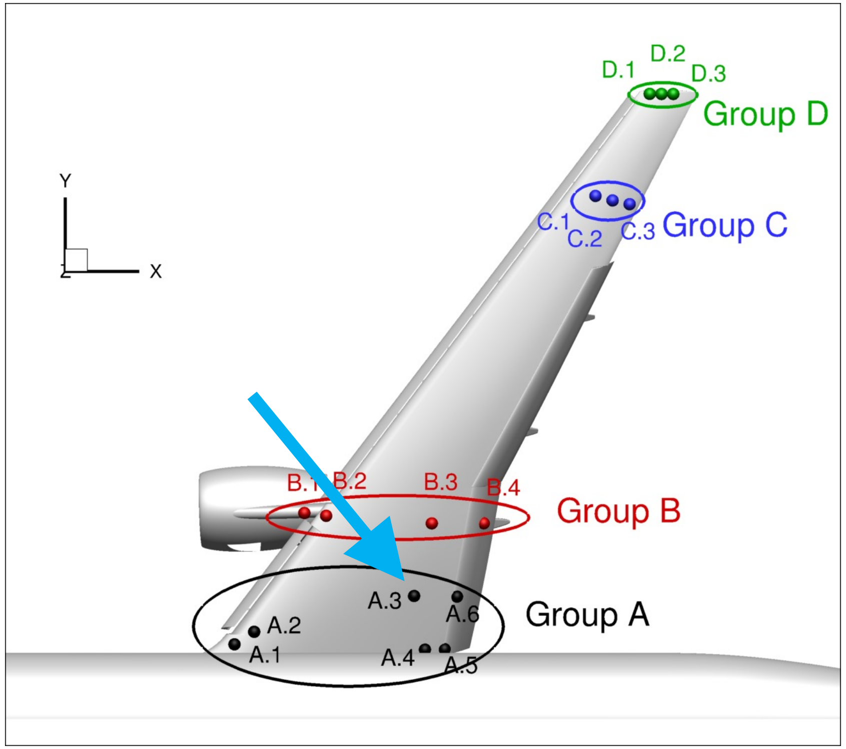
Looking for Trends in Velocity Profiles

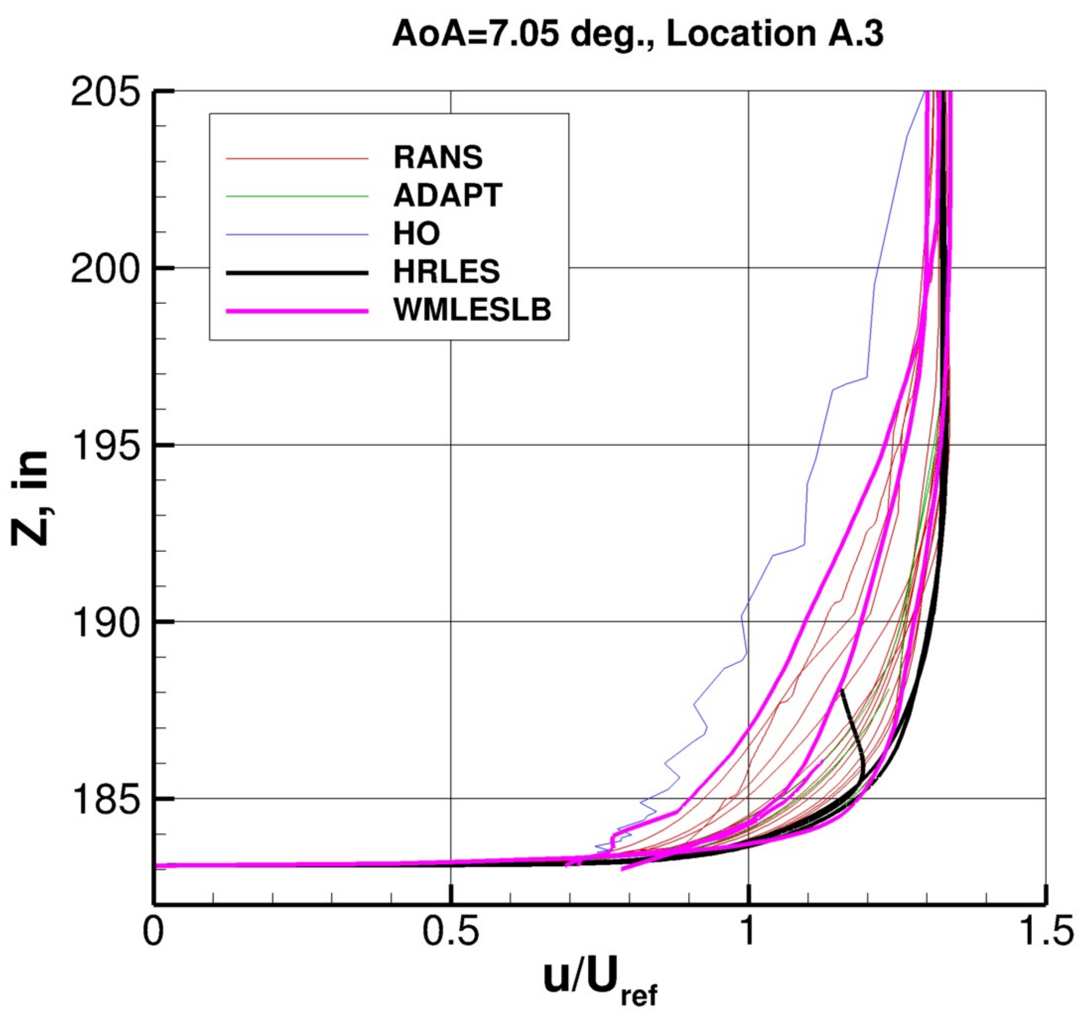




- No clear trends
- HO results do not look realistic
- WMLESLB results show wide variation

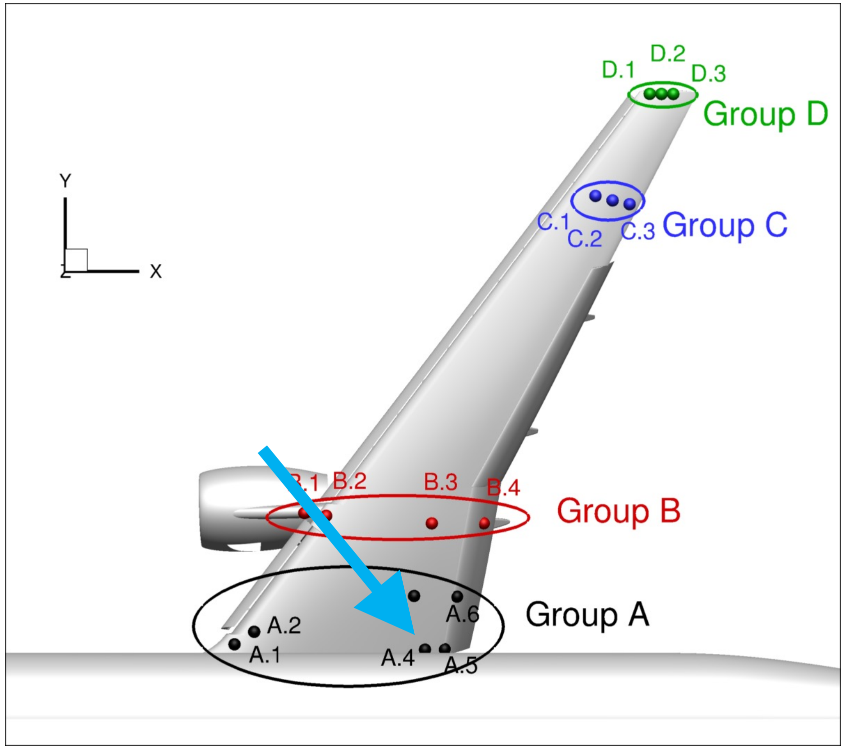
Looking for Trends in Velocity Profiles

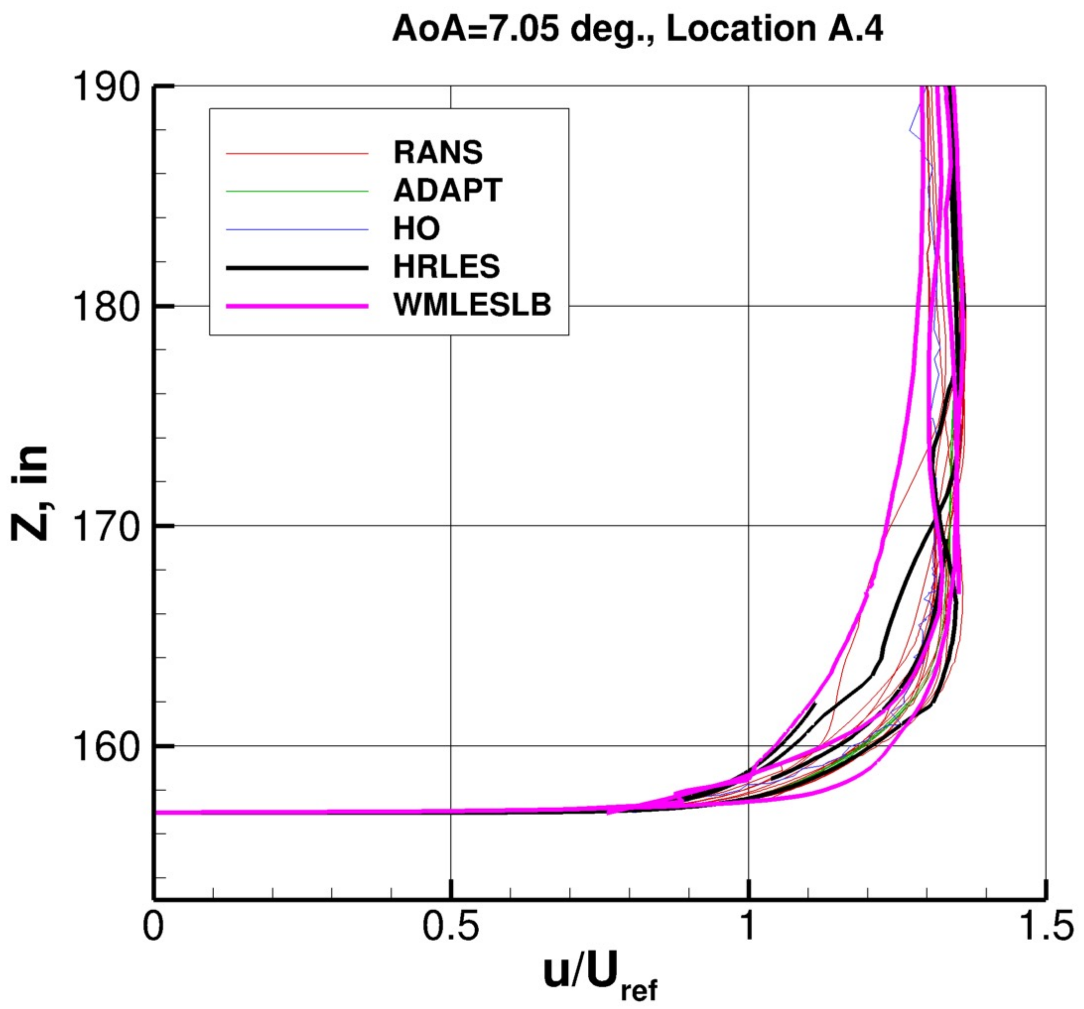




- No clear trends
- HO results do not look realistic
- L-005 has odd shape
- WMLESLB results show wide variation

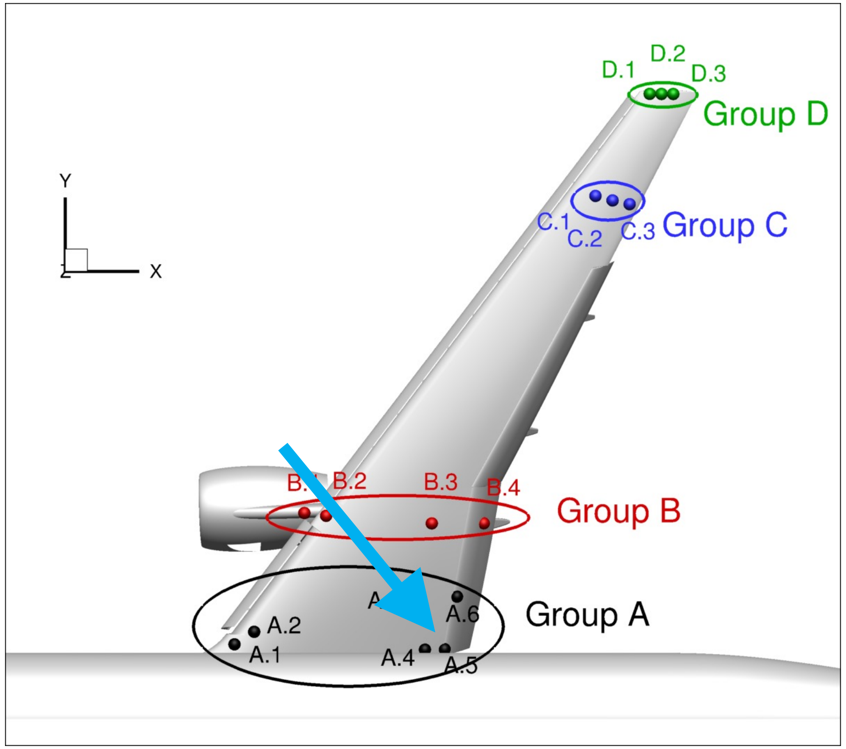
Looking for Trends in Velocity Profiles

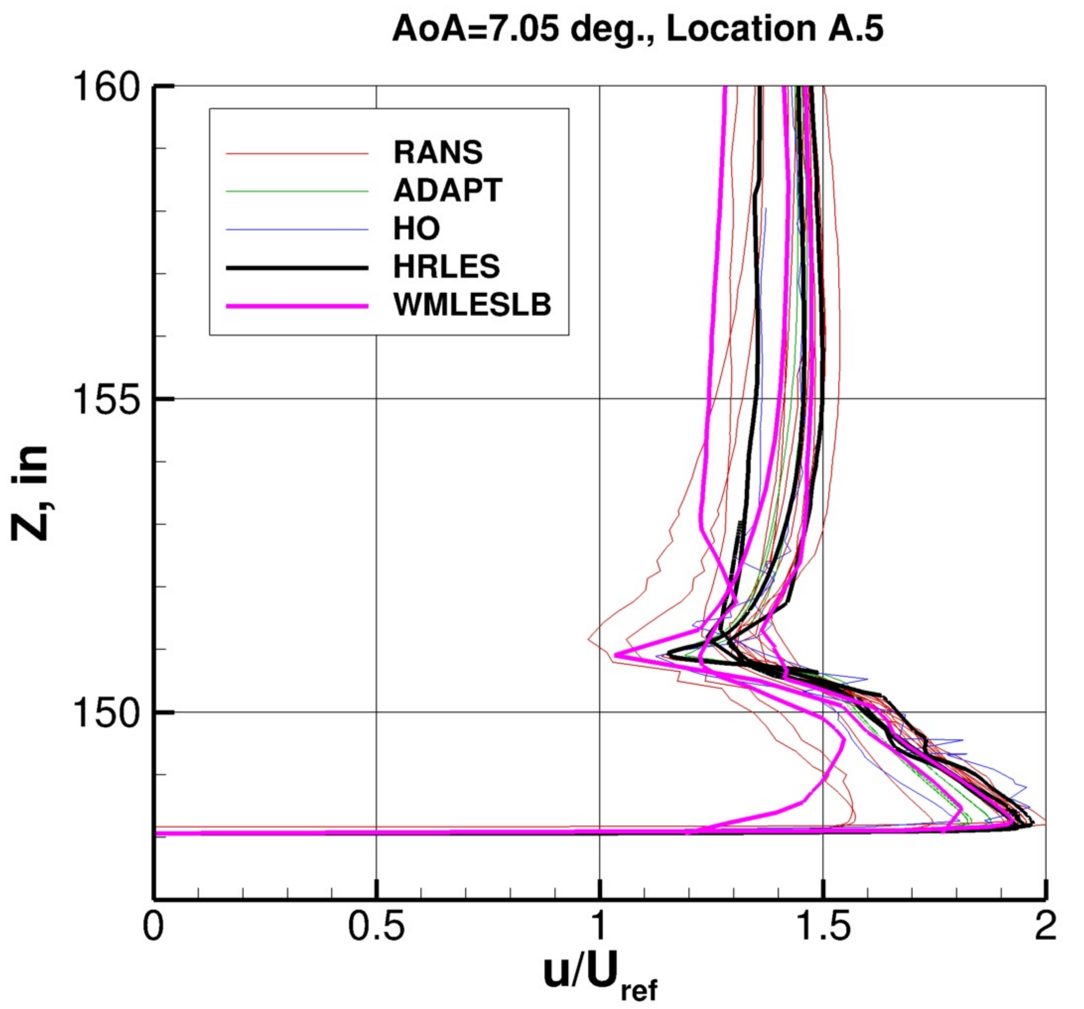




- Fairly consistent results, especially among RANS
- Outliers:
  - R-019.2, L-001.3, L-005, W-031, and W-047

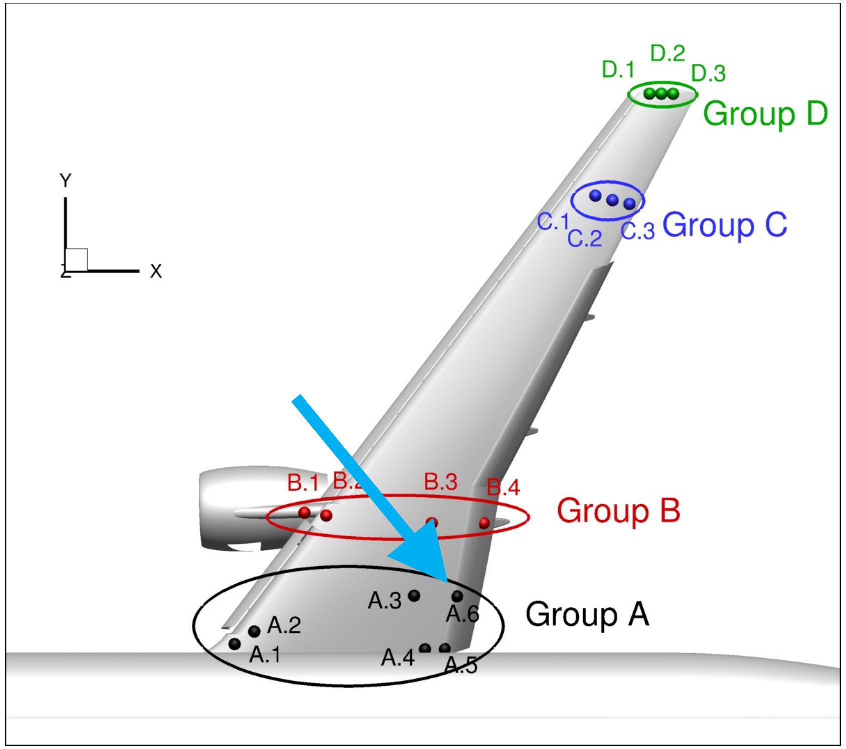
Looking for Trends in Velocity Profiles

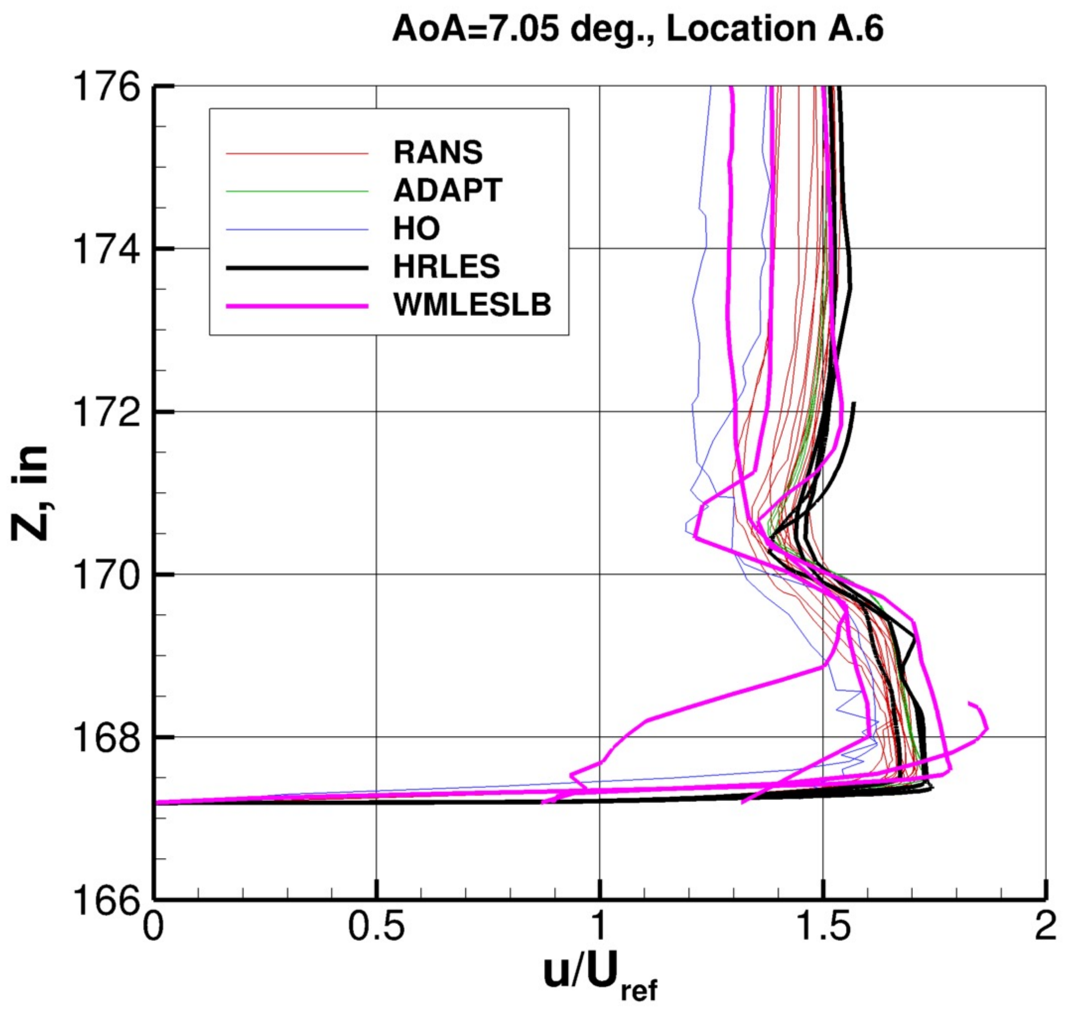




- Somewhat consistent results, except for a few outliers:
  - R-059.3, R-059.4, and W-047
  - HO has "wiggles"

Looking for Trends in Velocity Profiles





- Somewhat consistent results, except for a few outliers:
  - HO results
  - WMLESLB results show wide variation

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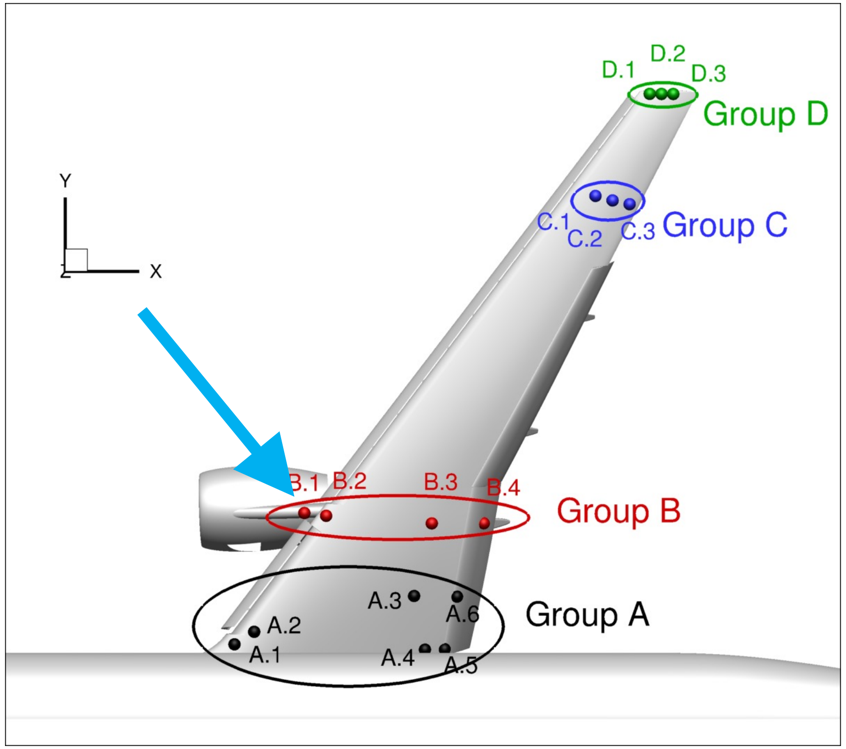
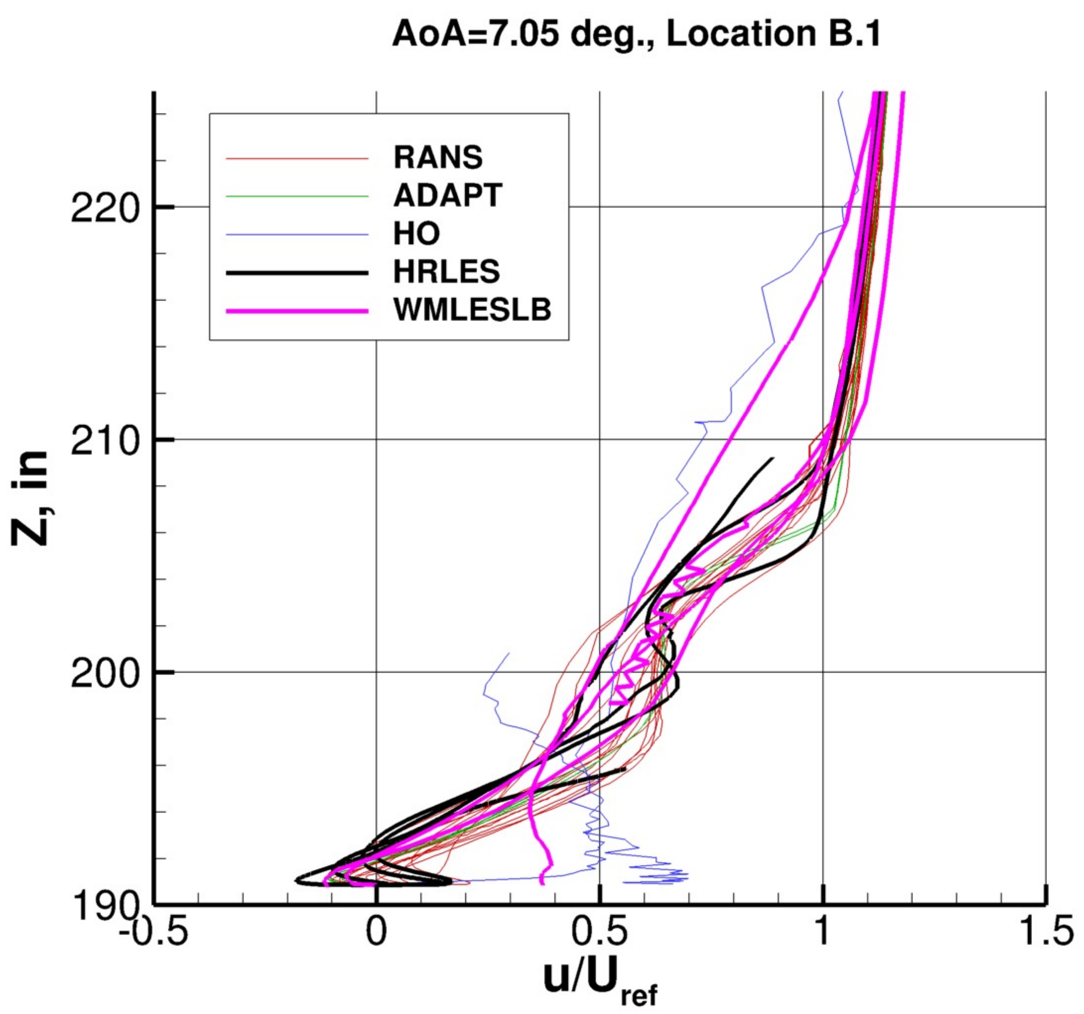
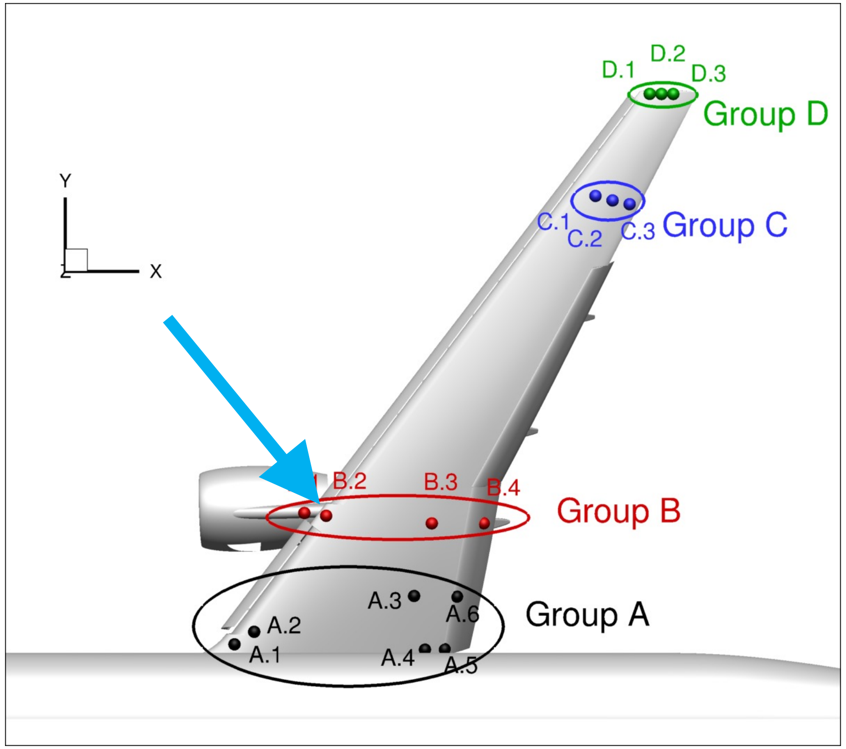
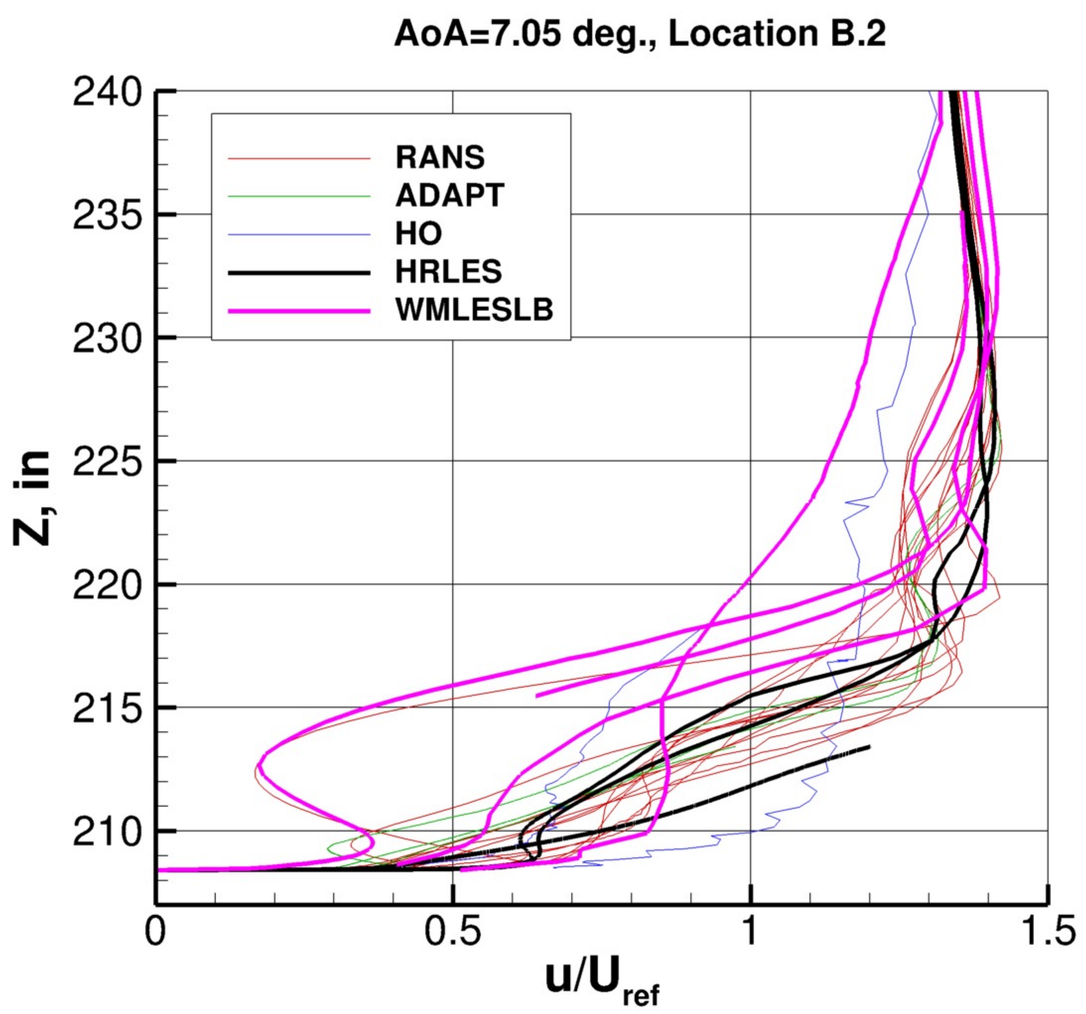




- Somewhat consistent results, except for a few outliers:
  - HO results
  - W-047
  - W-020.3 has “wiggles”

Looking for Trends in Velocity Profiles





- No clear trends
- HO results have “wiggles”
- WMLESLB results show wide variation

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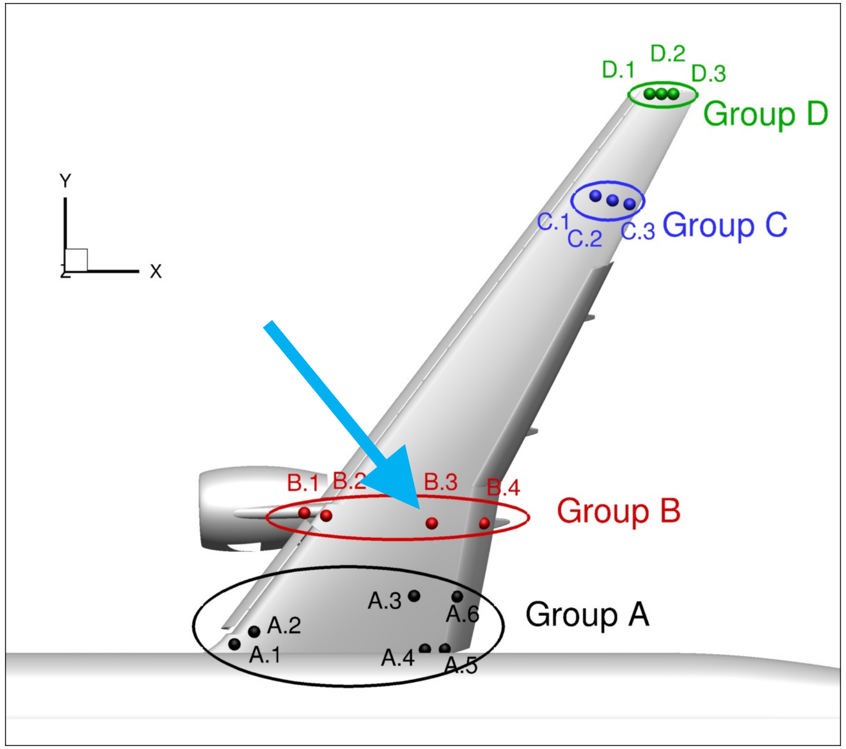

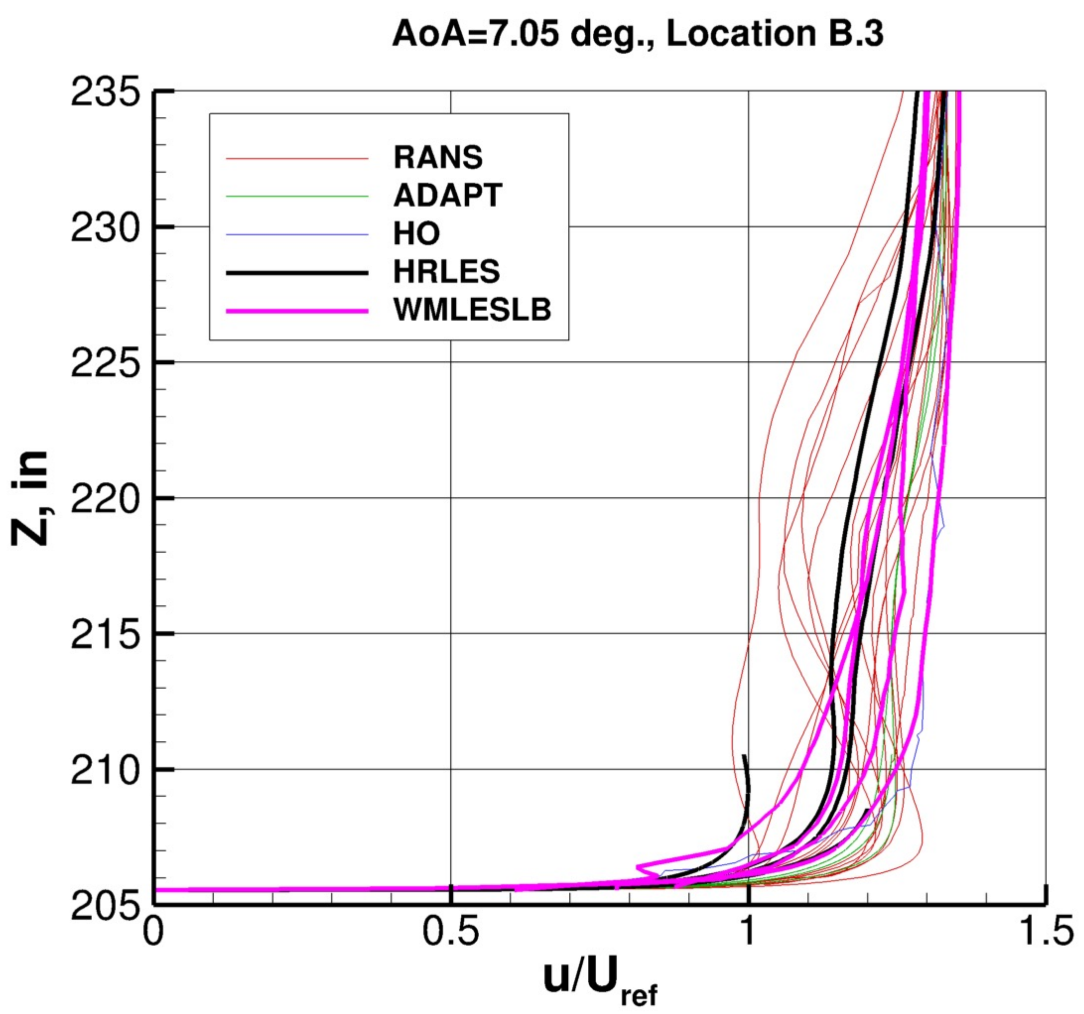

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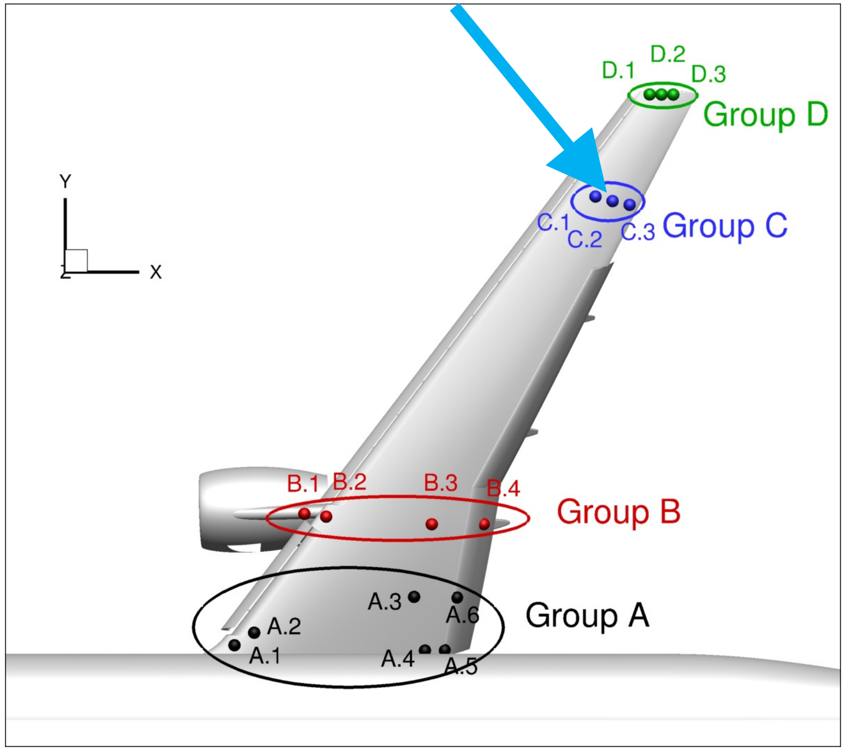
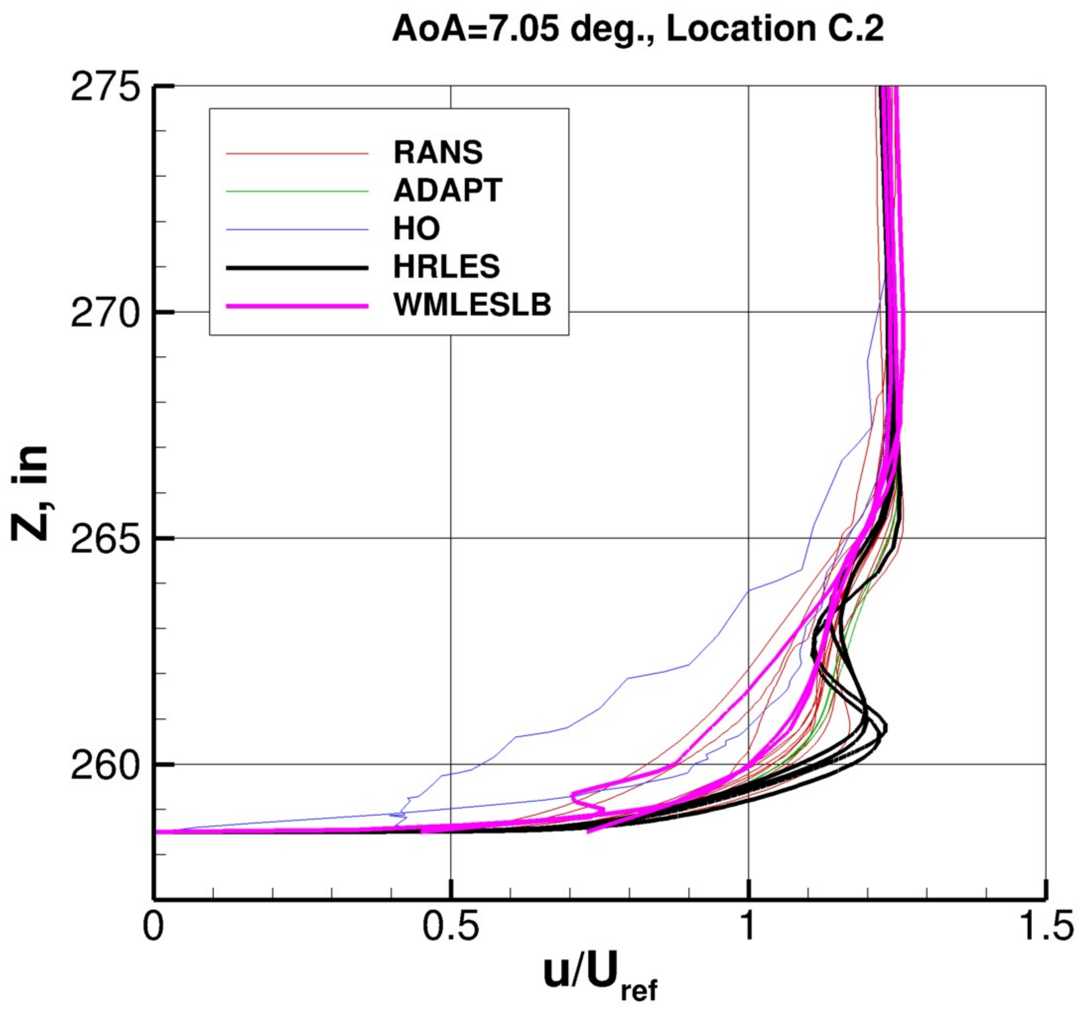
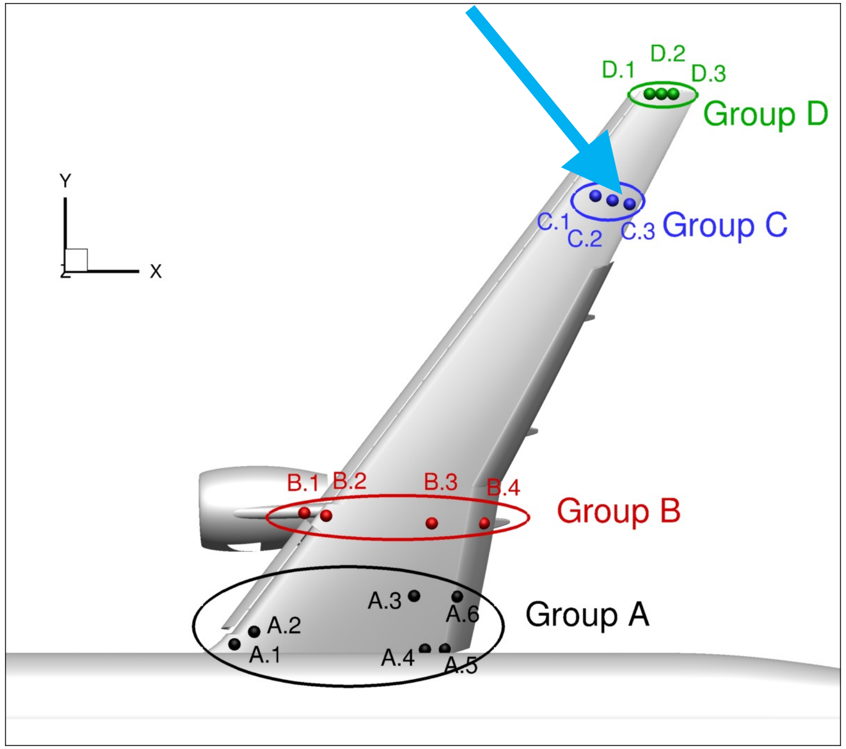
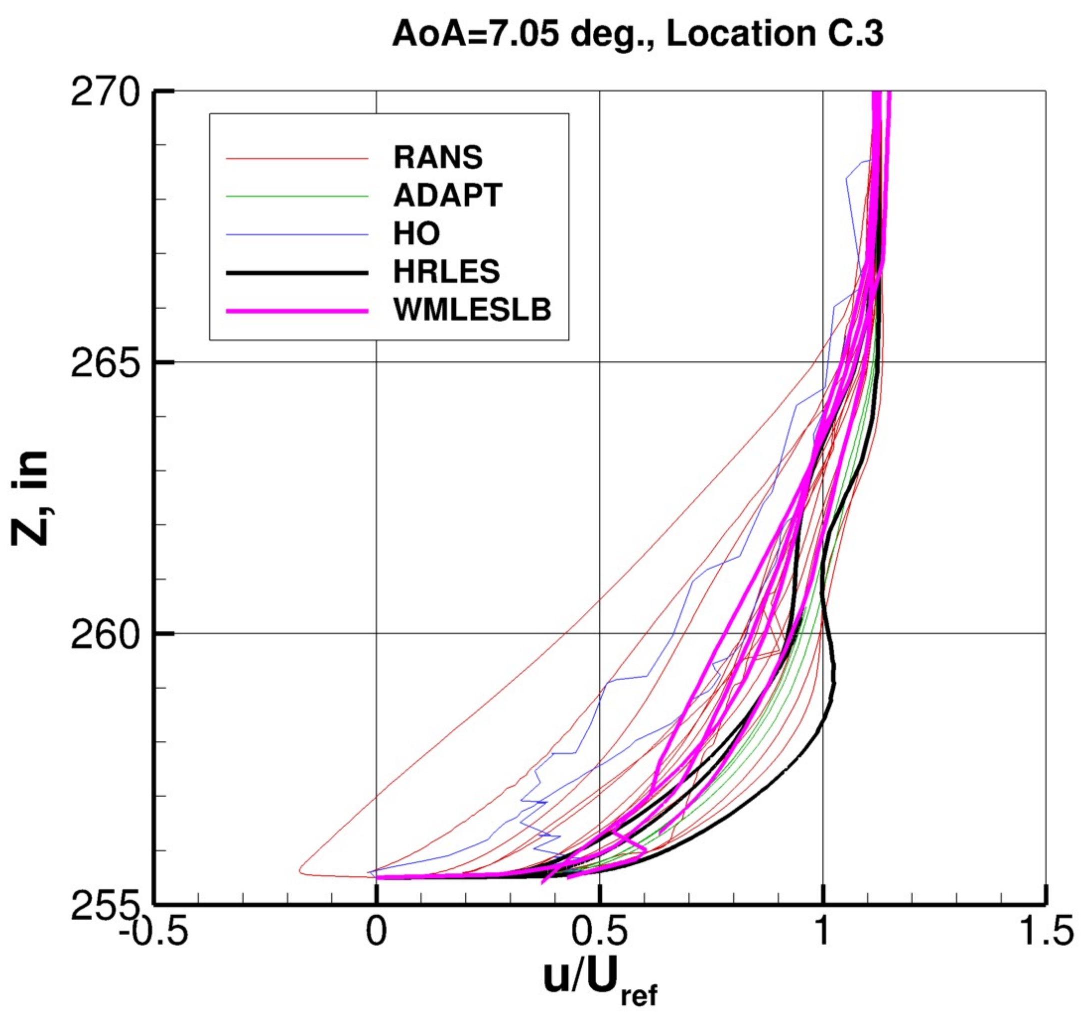




- RANS shows somewhat larger variation
- All HRLES generally similar
- WMLESLB generally similar except for W-047
- HO has “wiggles”; results are different

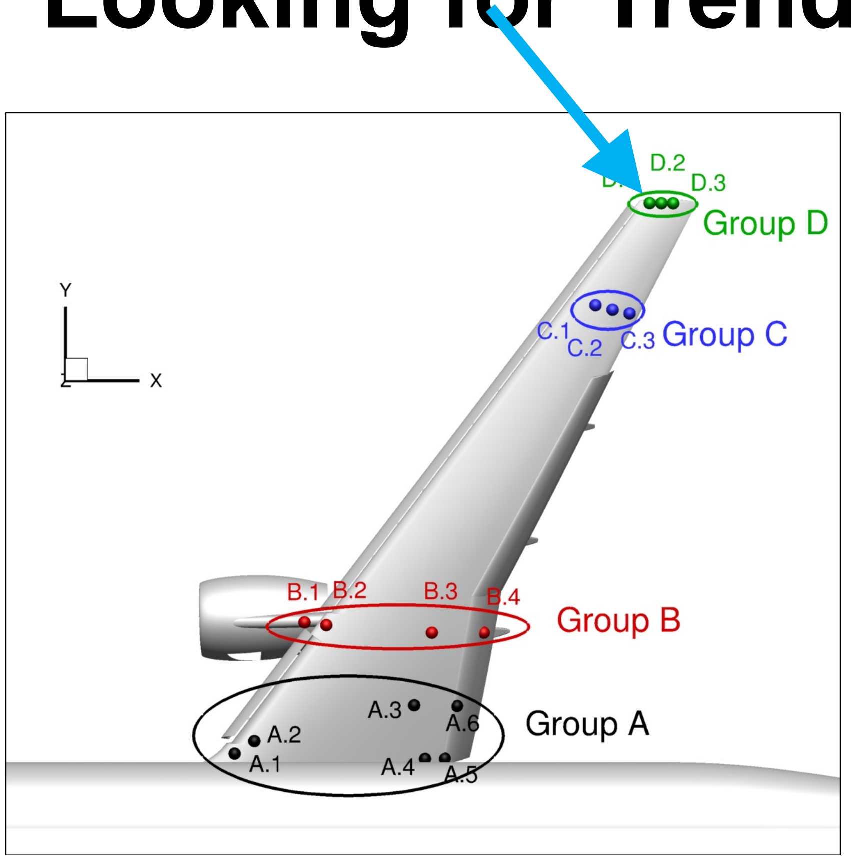
Looking for Trends in Velocity Profiles

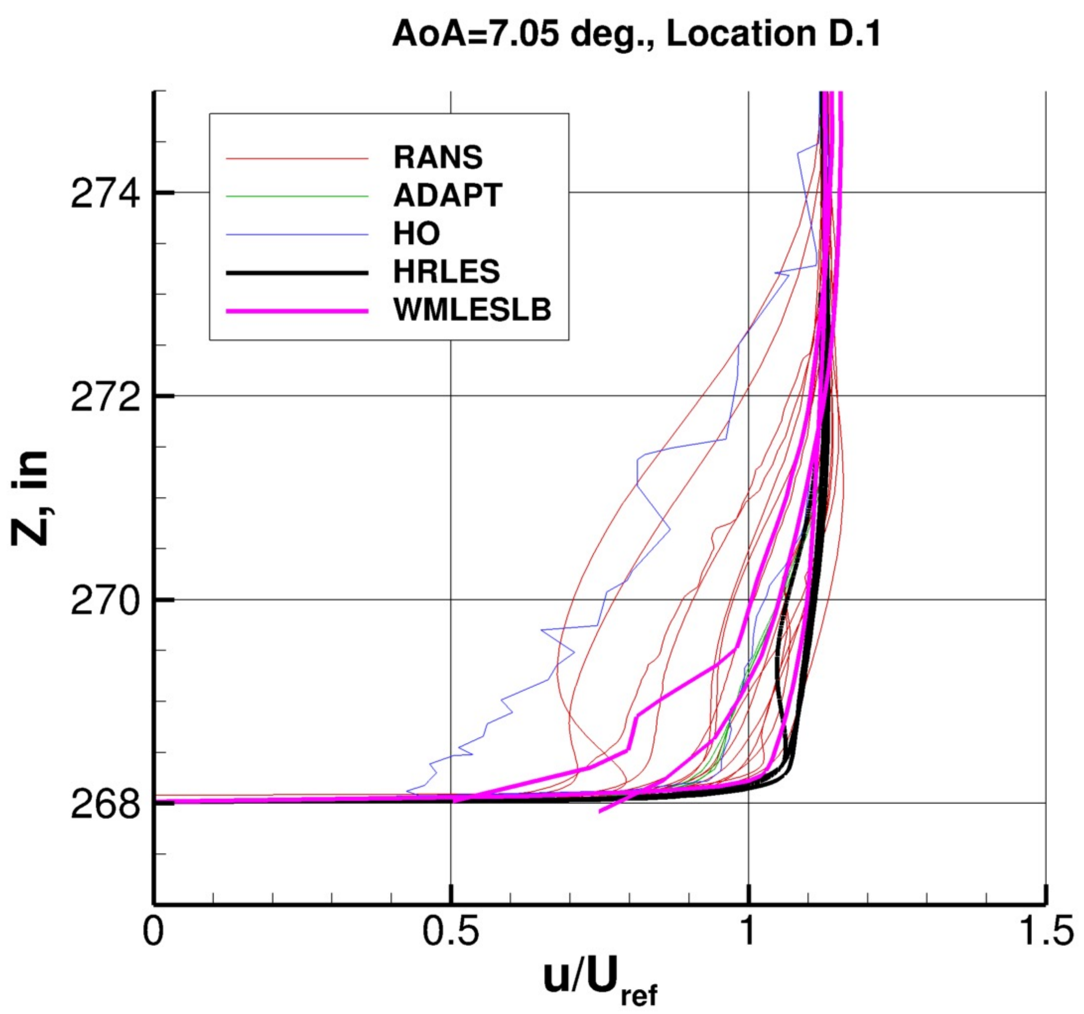




- No clear trends; very large variation among RANS

Looking for Trends in Velocity Profiles





- No clear trends, except HRLES are somewhat similar

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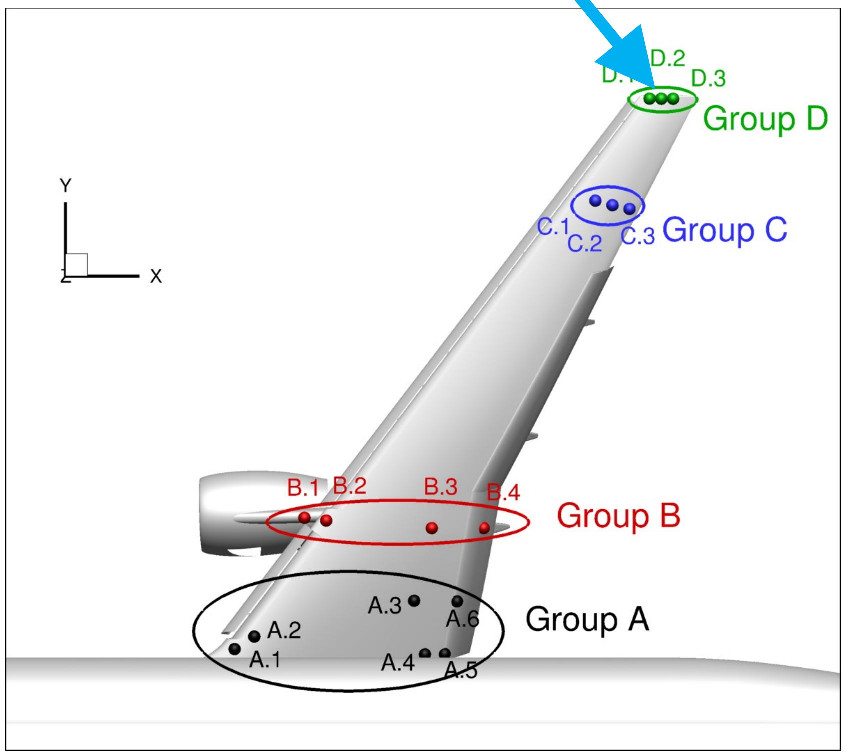

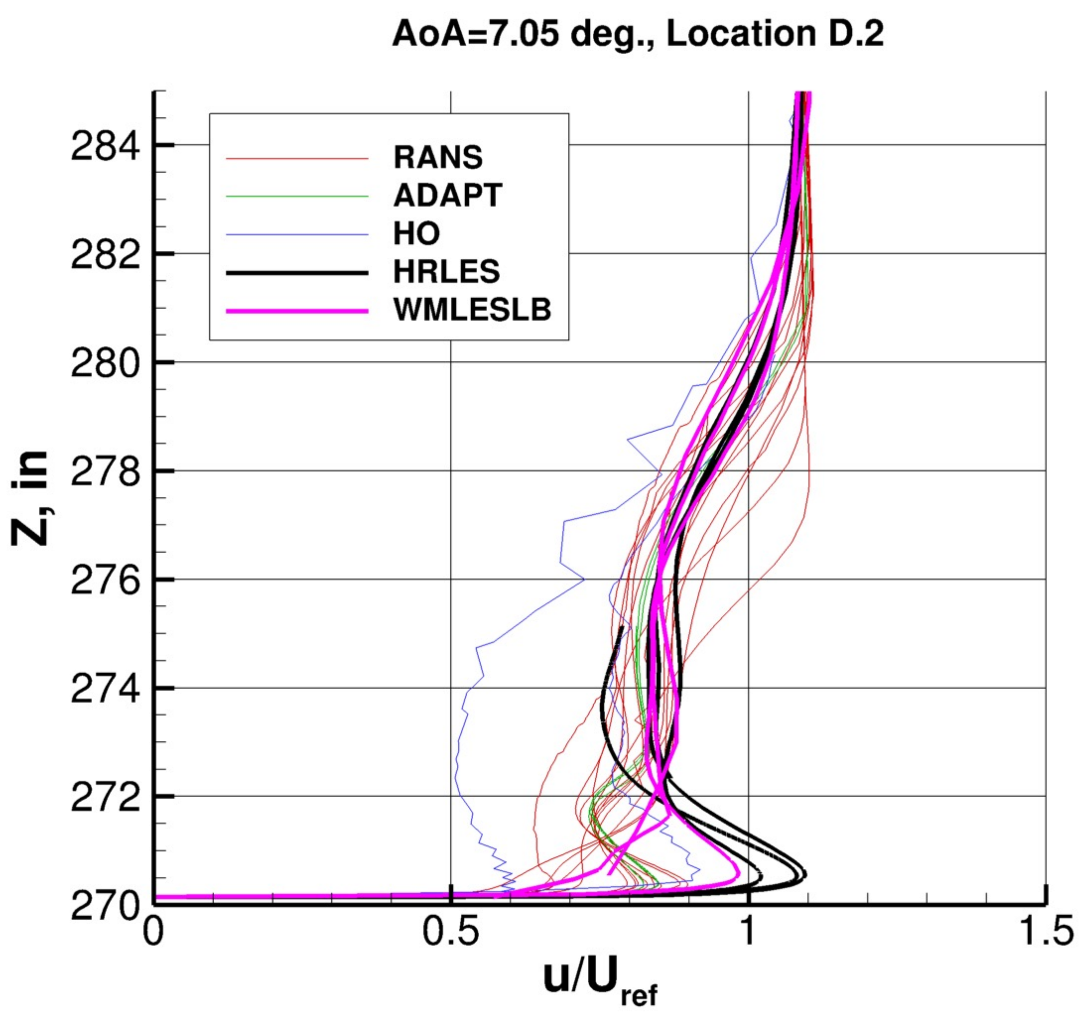

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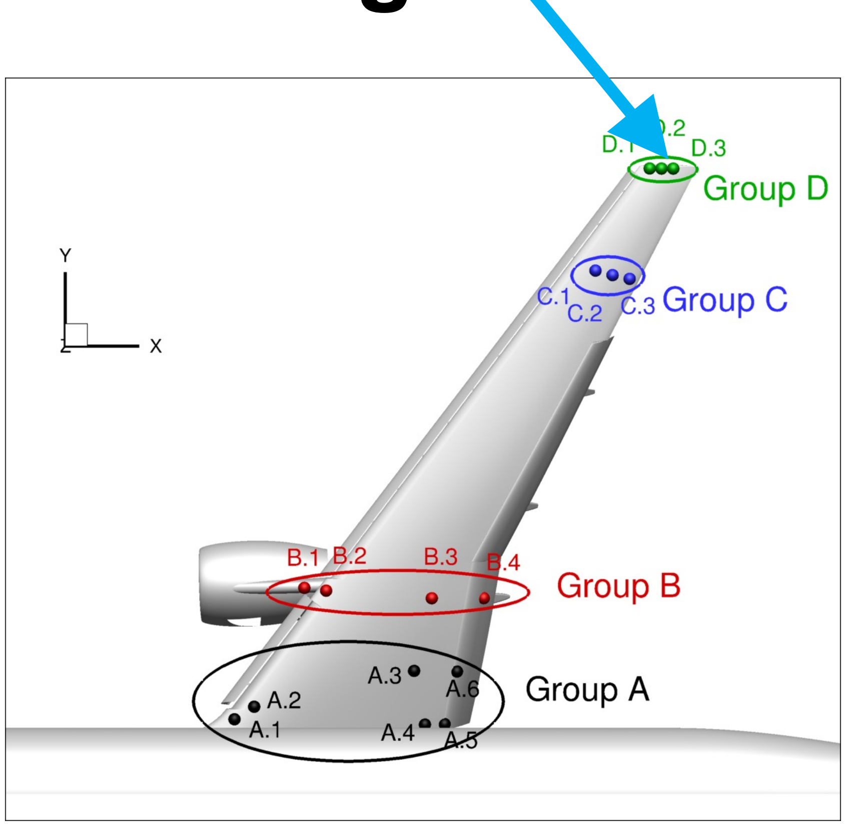
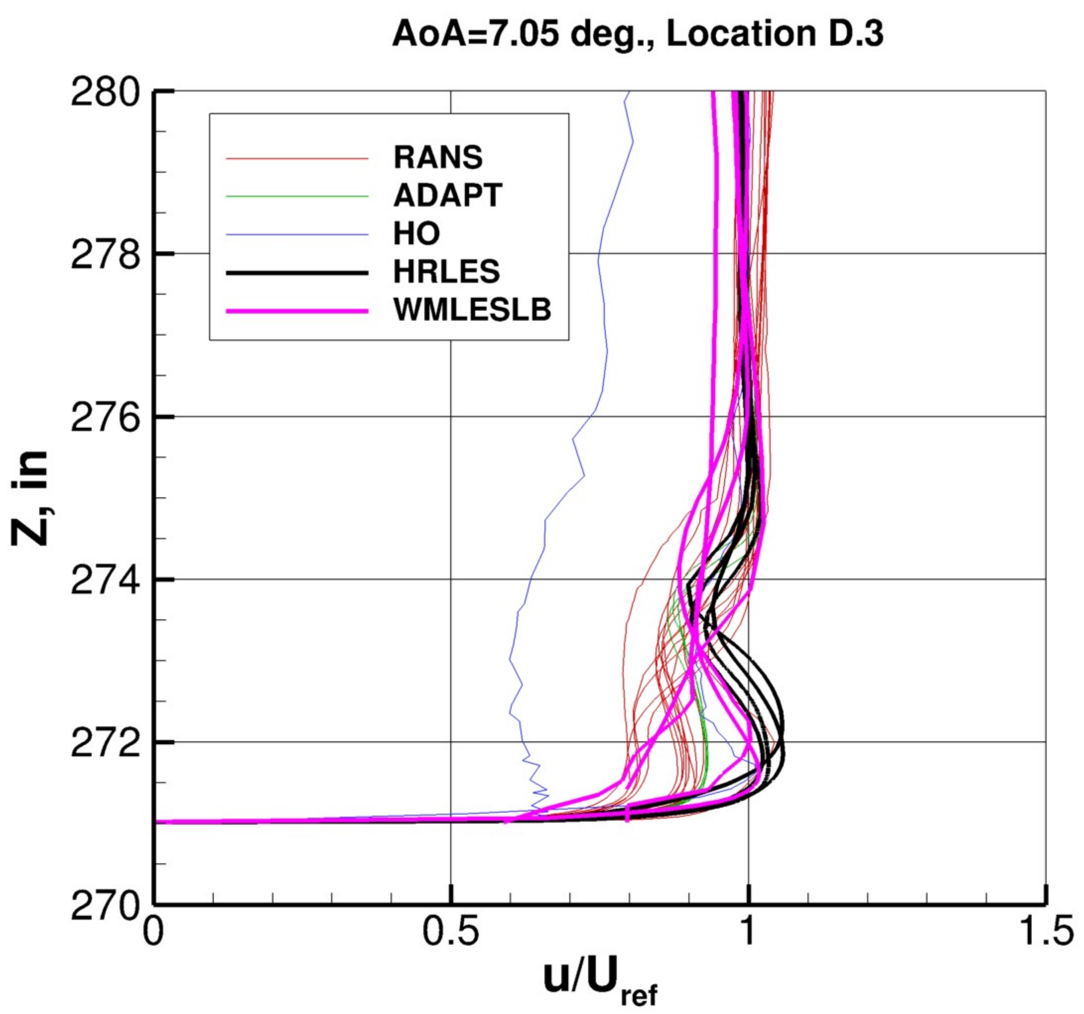
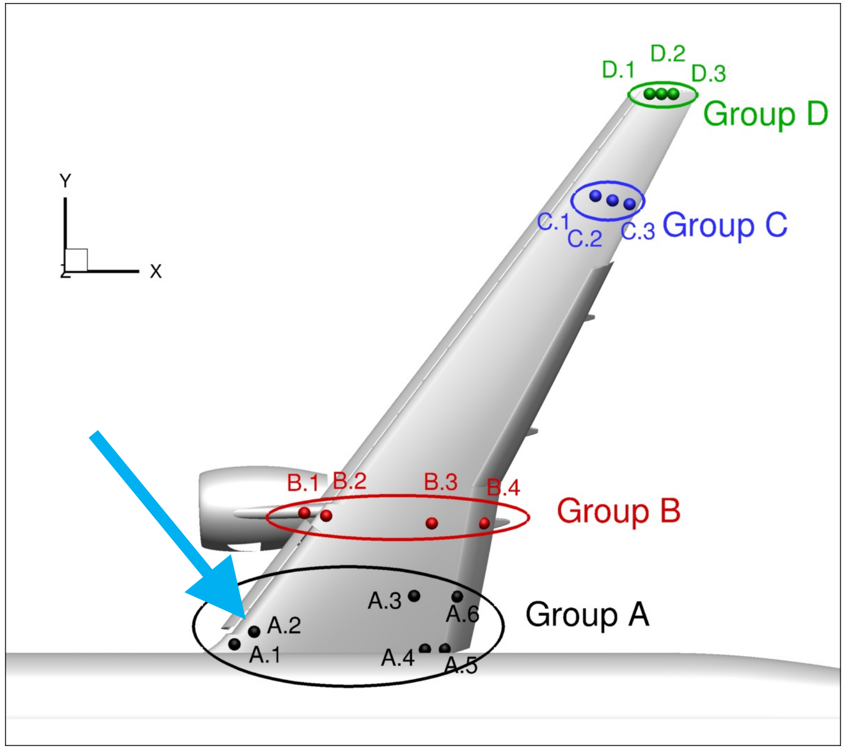
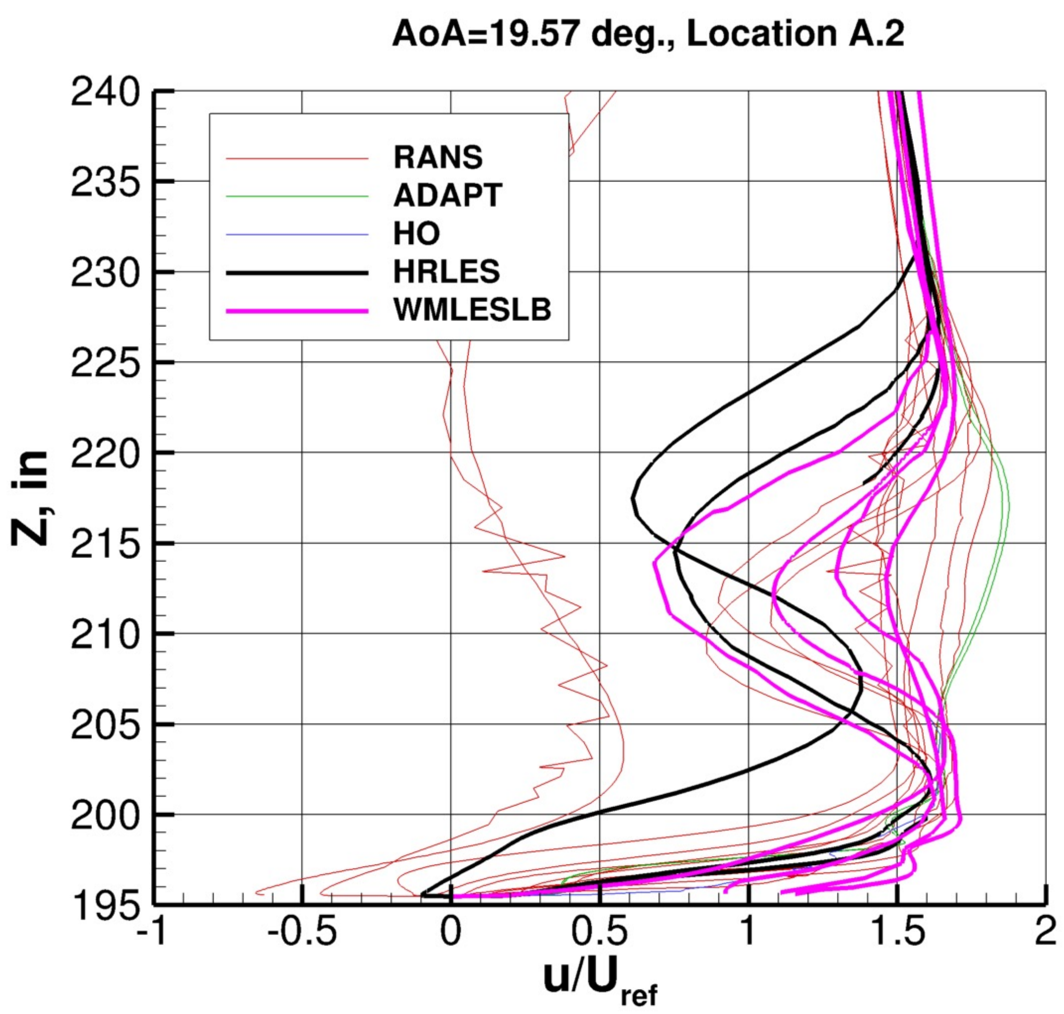




- No clear trends, except HRLES are somewhat similar
  - There seems to be 3 “clusters” of solutions

Looking for Trends in Velocity Profiles





- No clear trends

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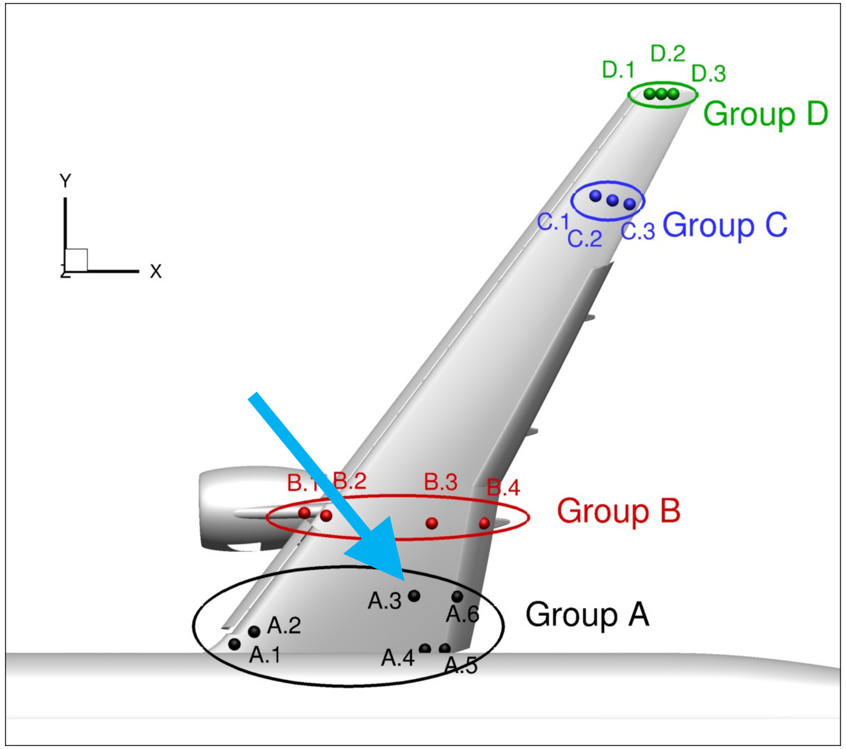

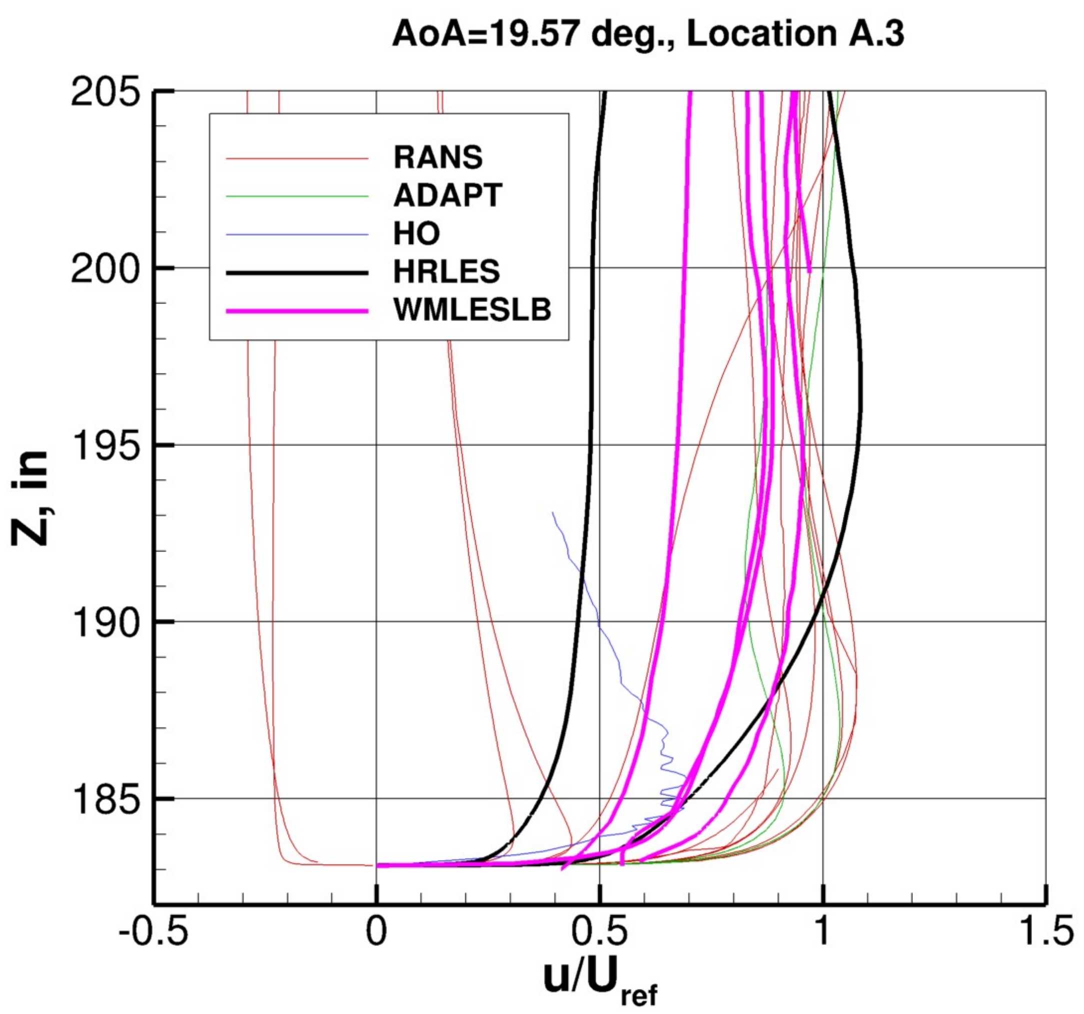

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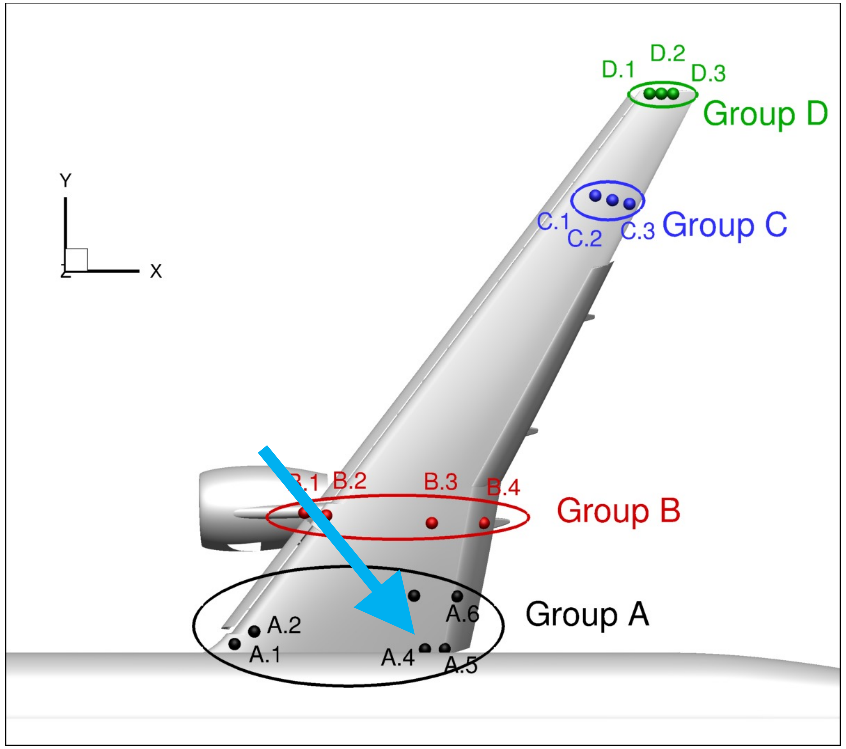

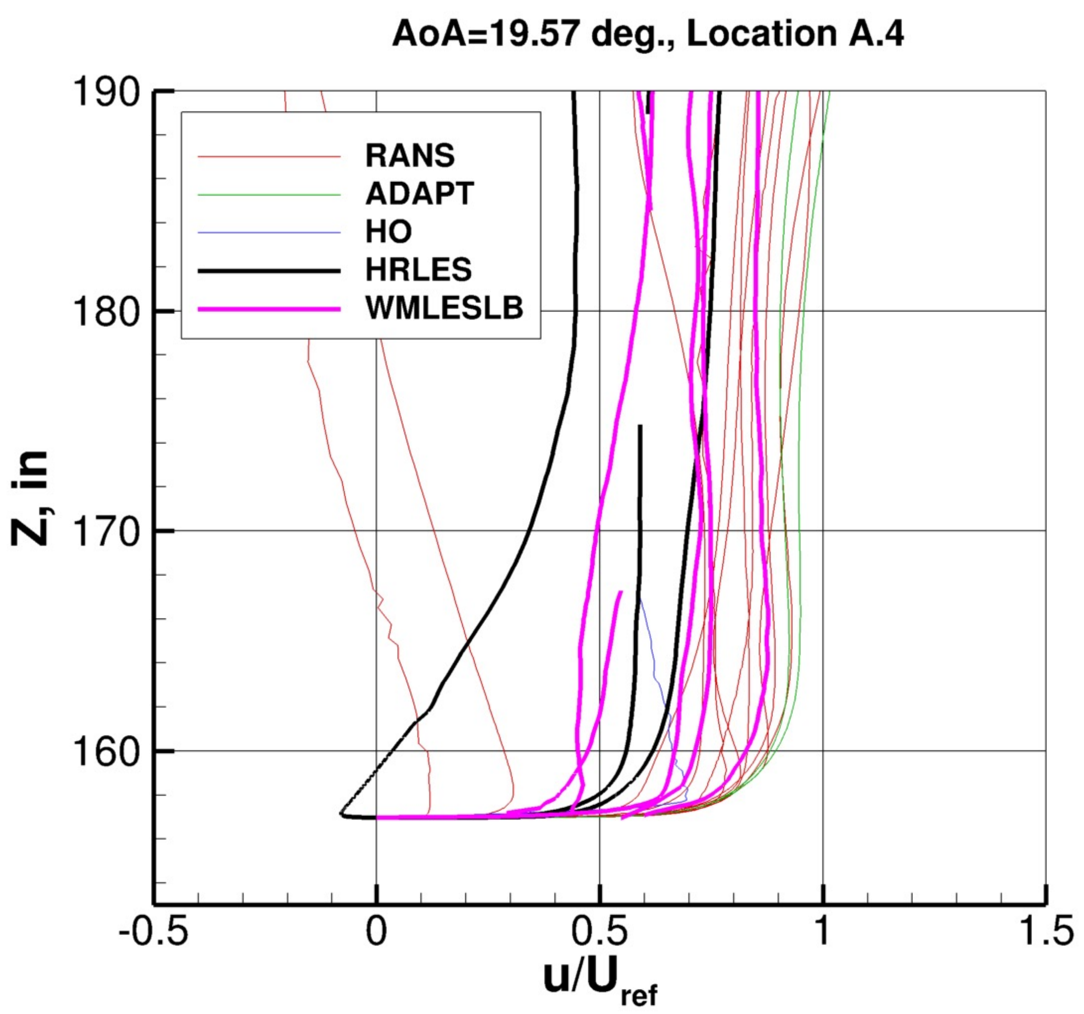

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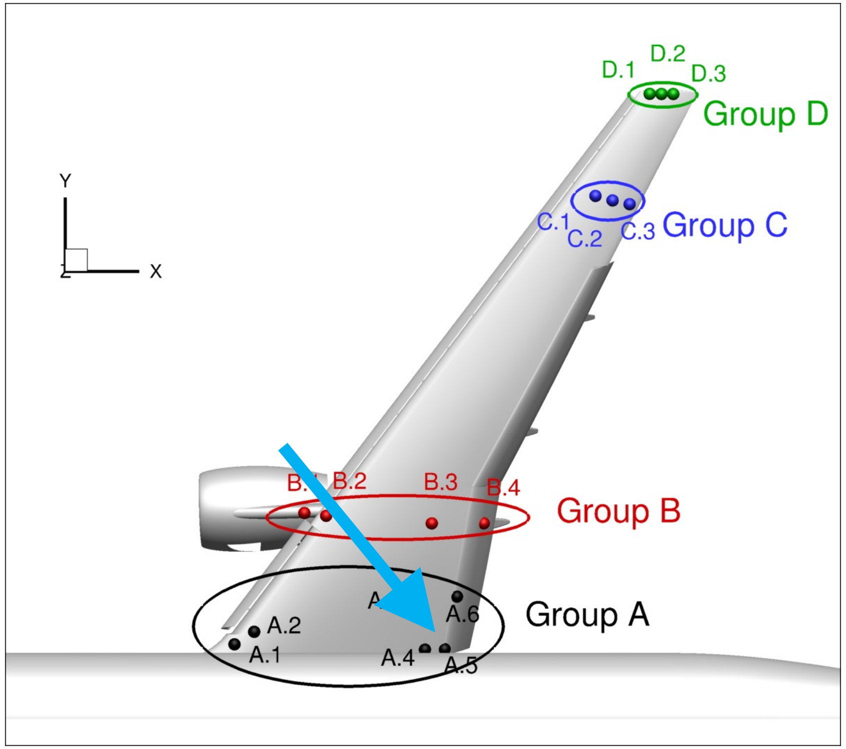

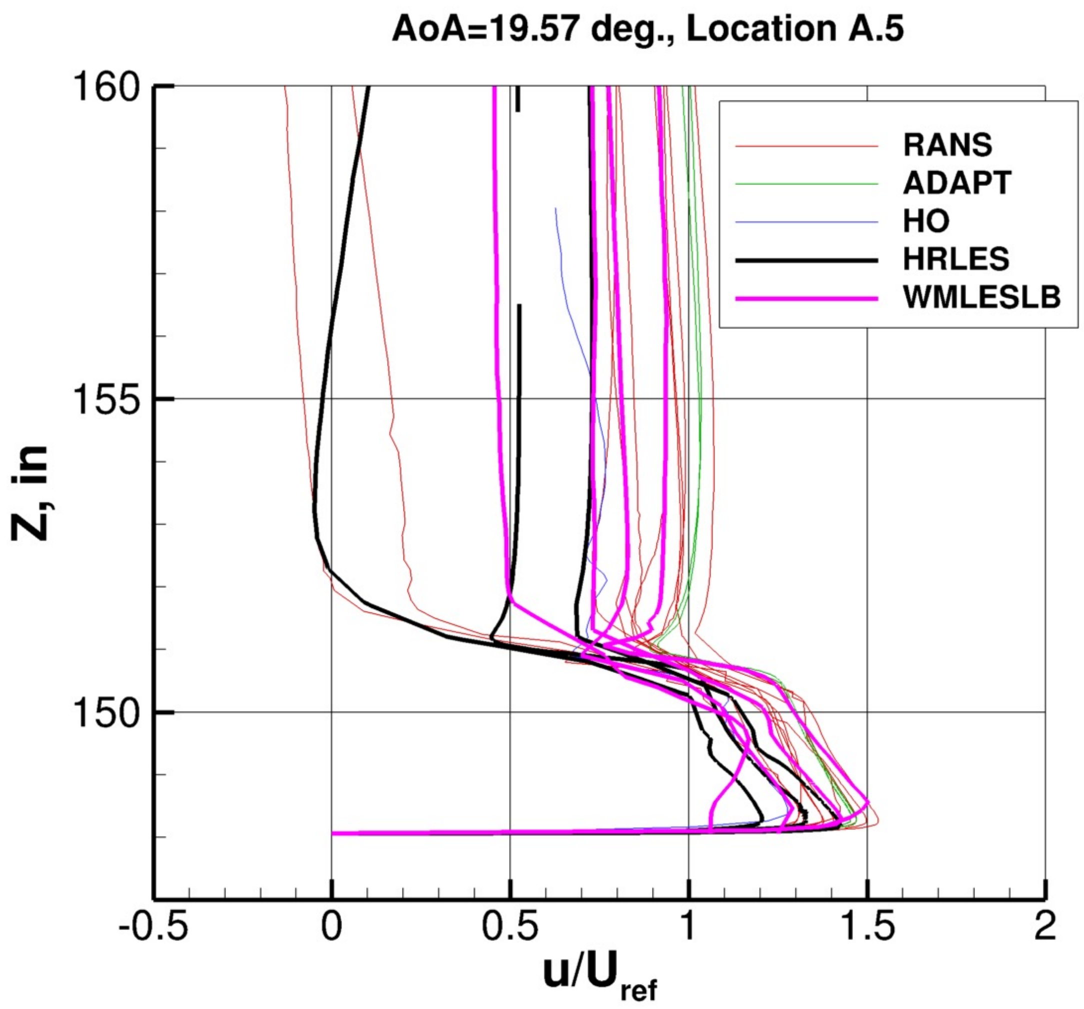

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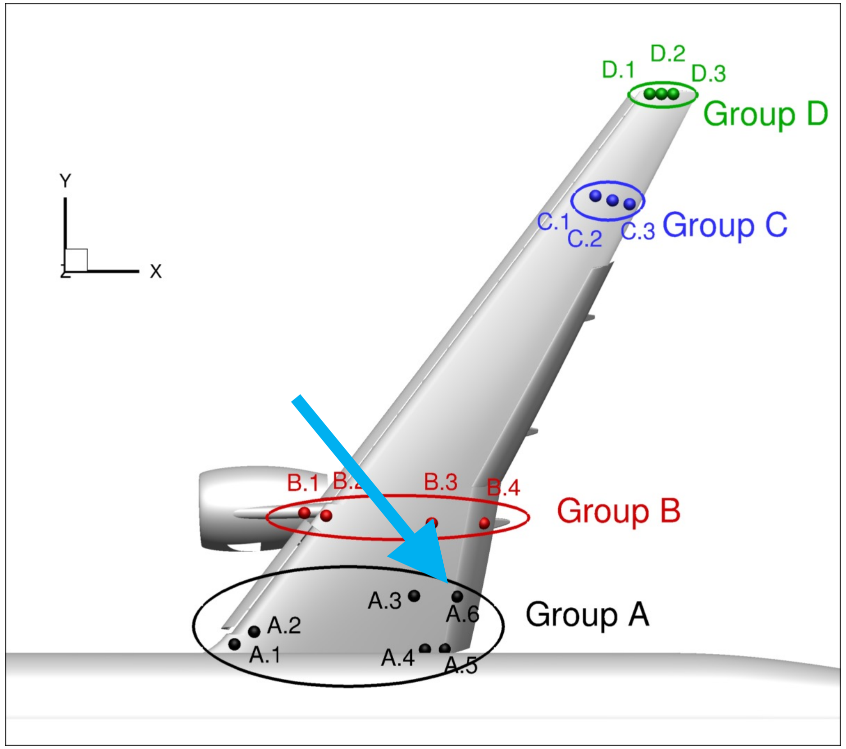

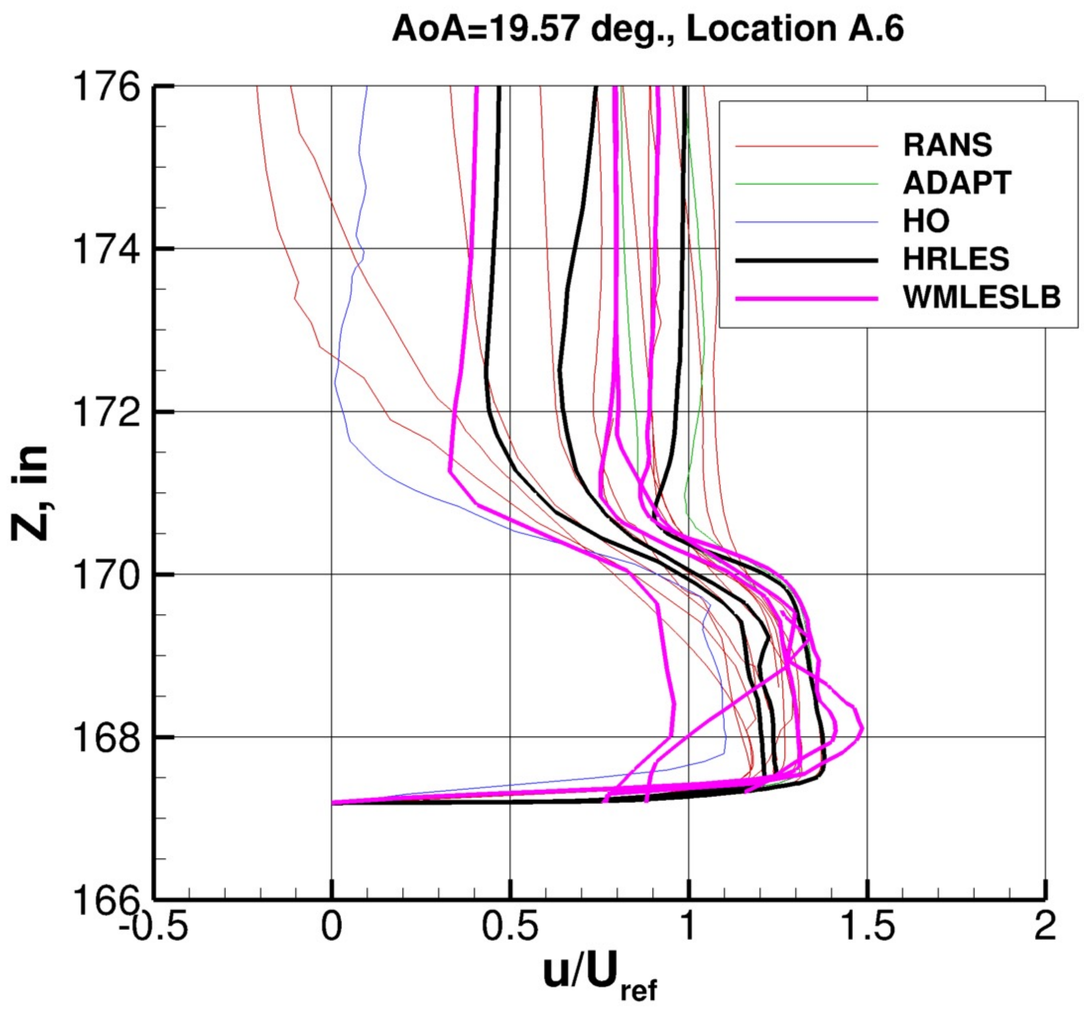

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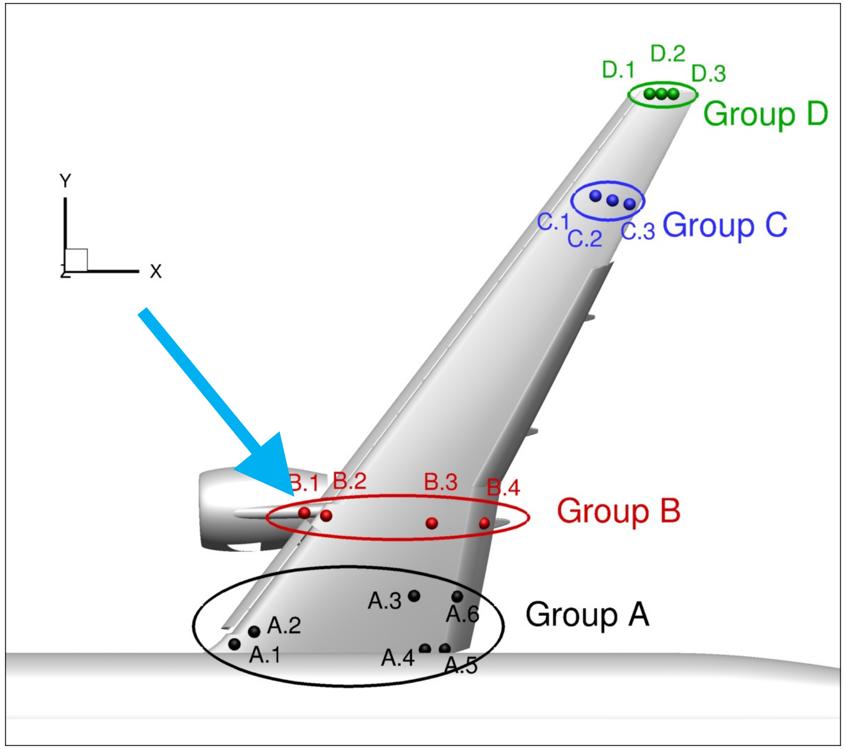
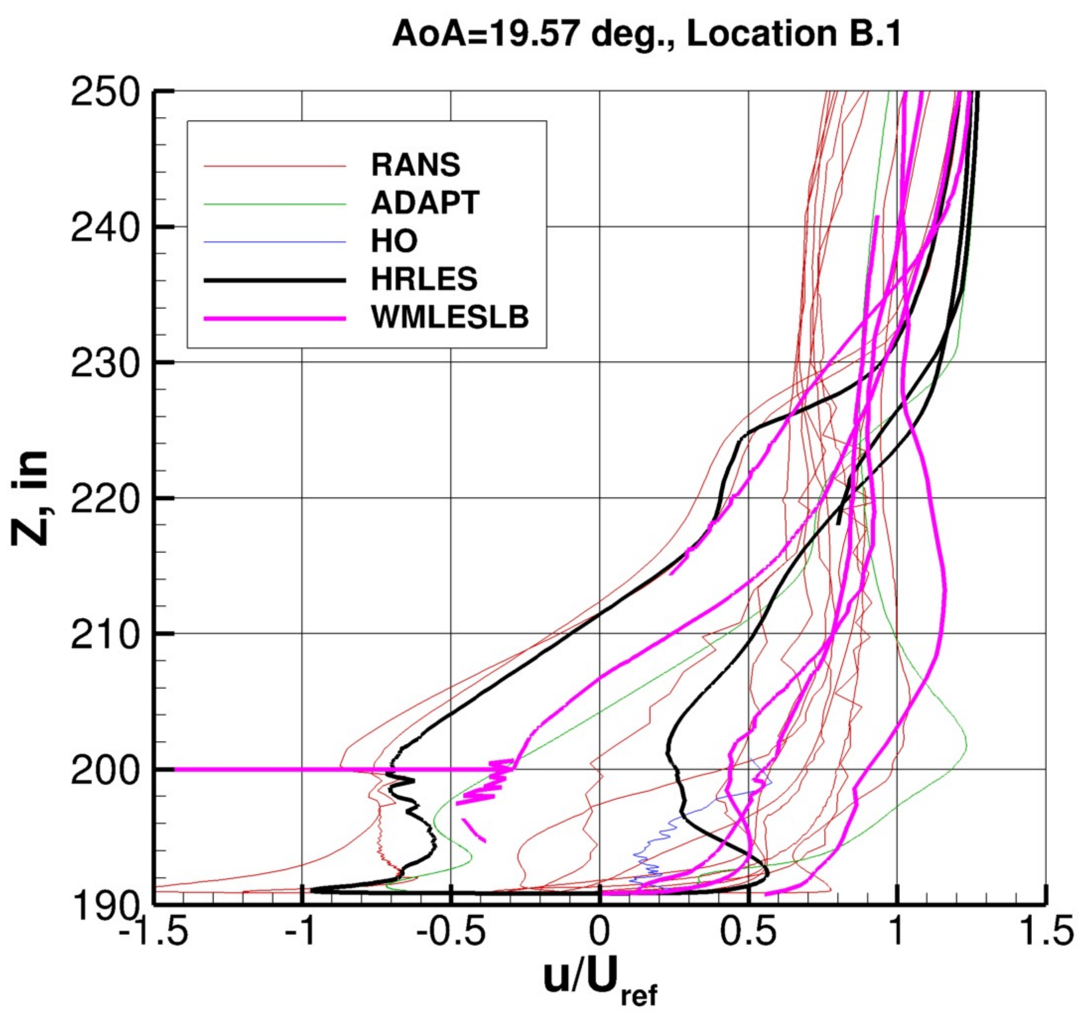
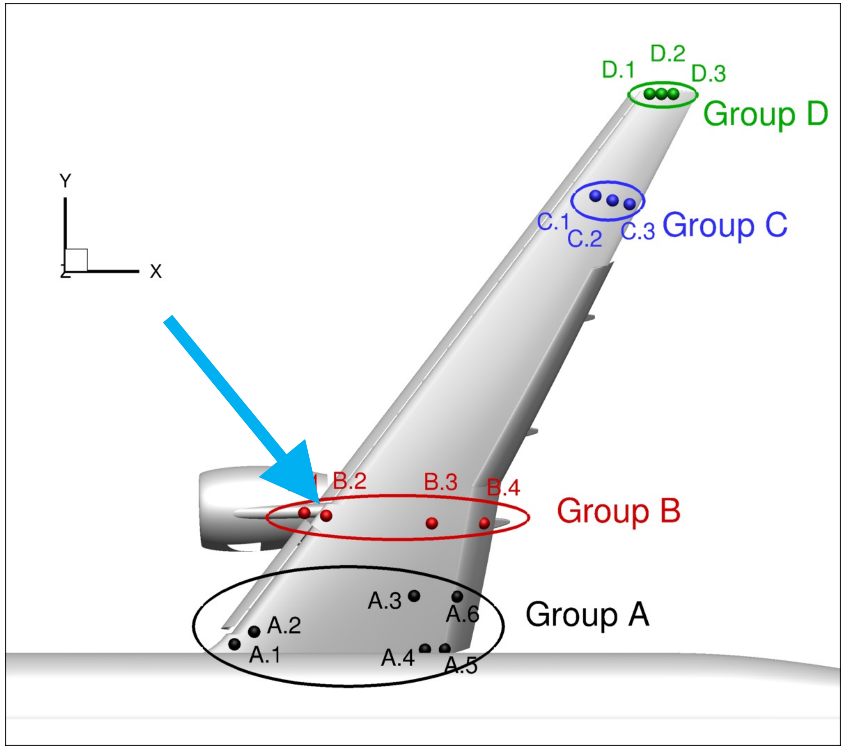
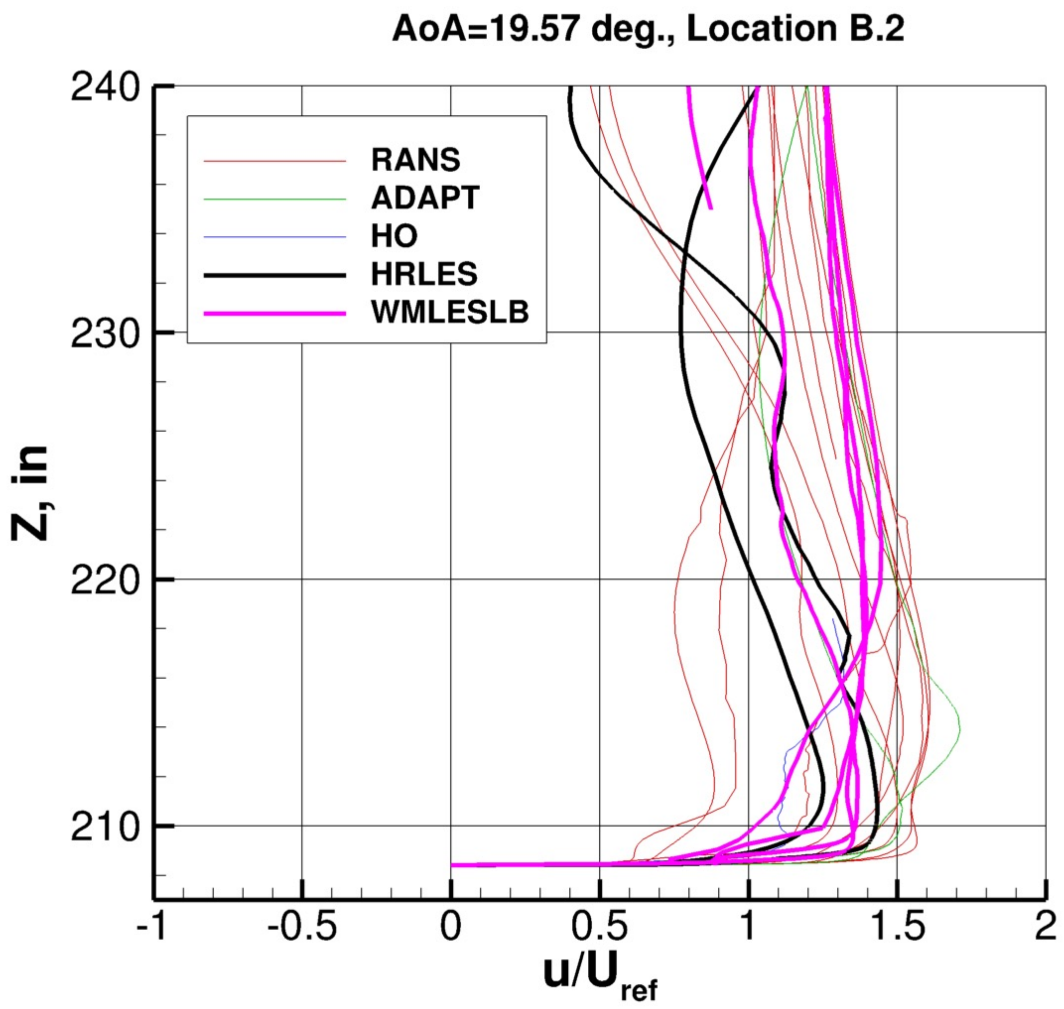




- No clear trends

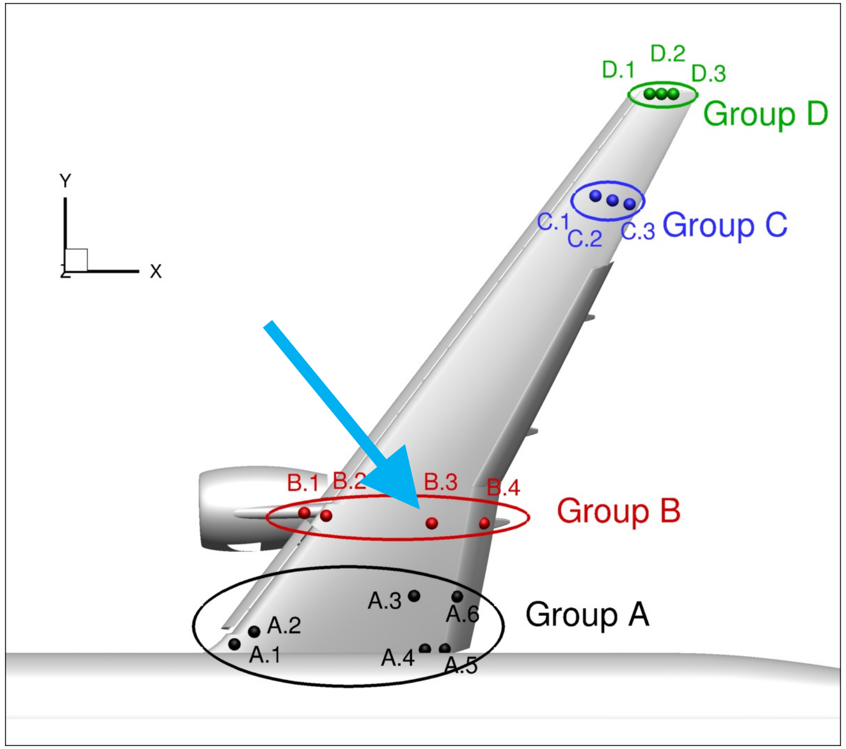
Looking for Trends in Velocity Profiles

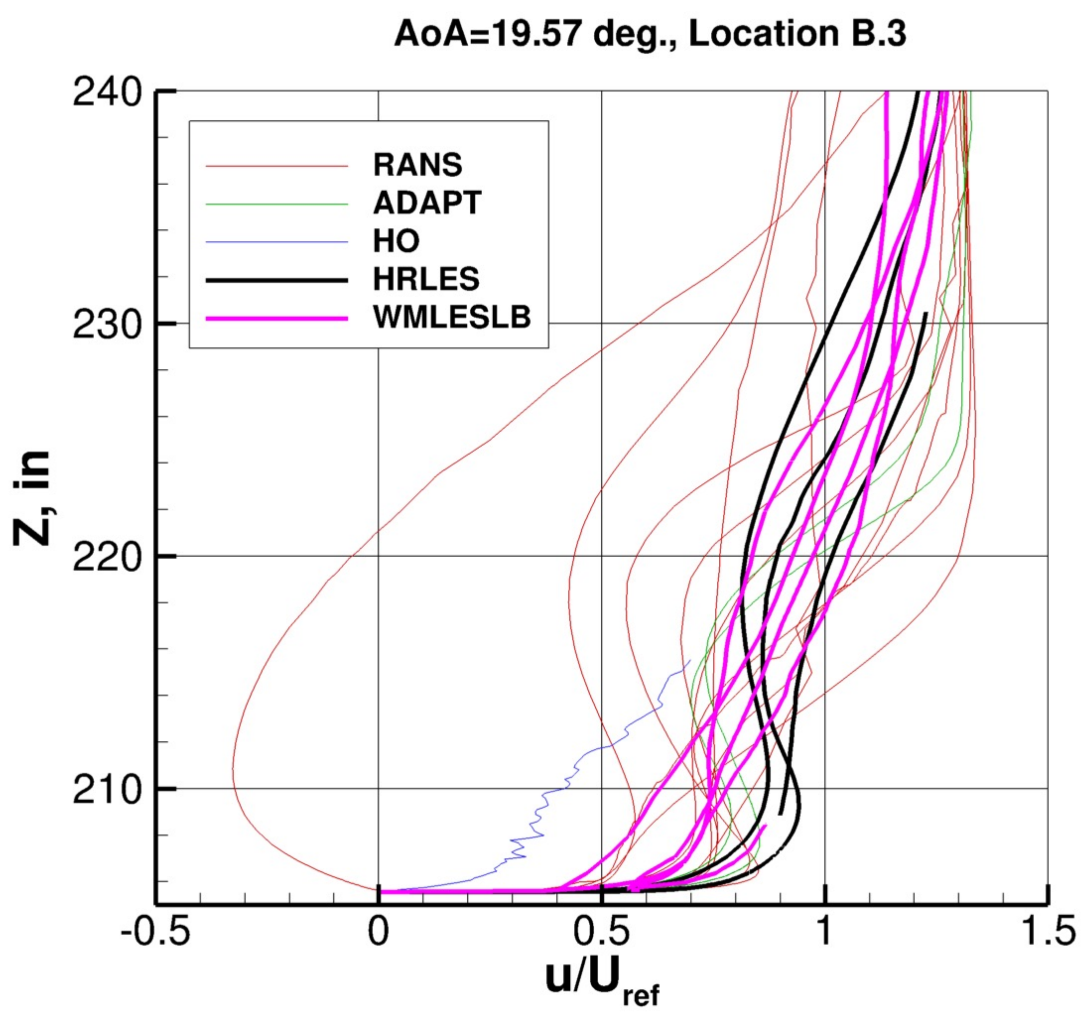




- No clear trends

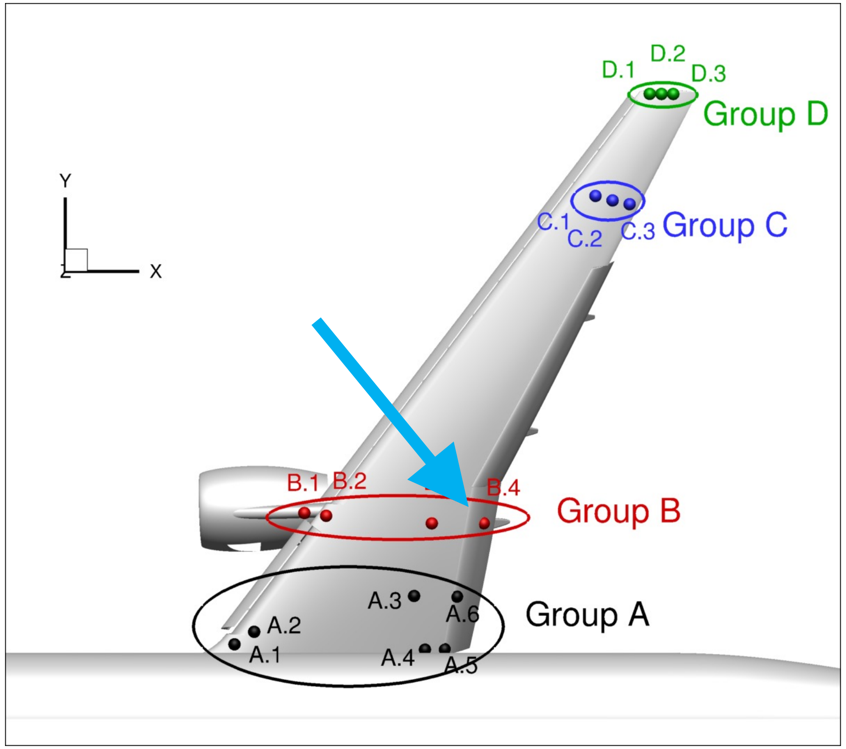
Looking for Trends in Velocity Profiles



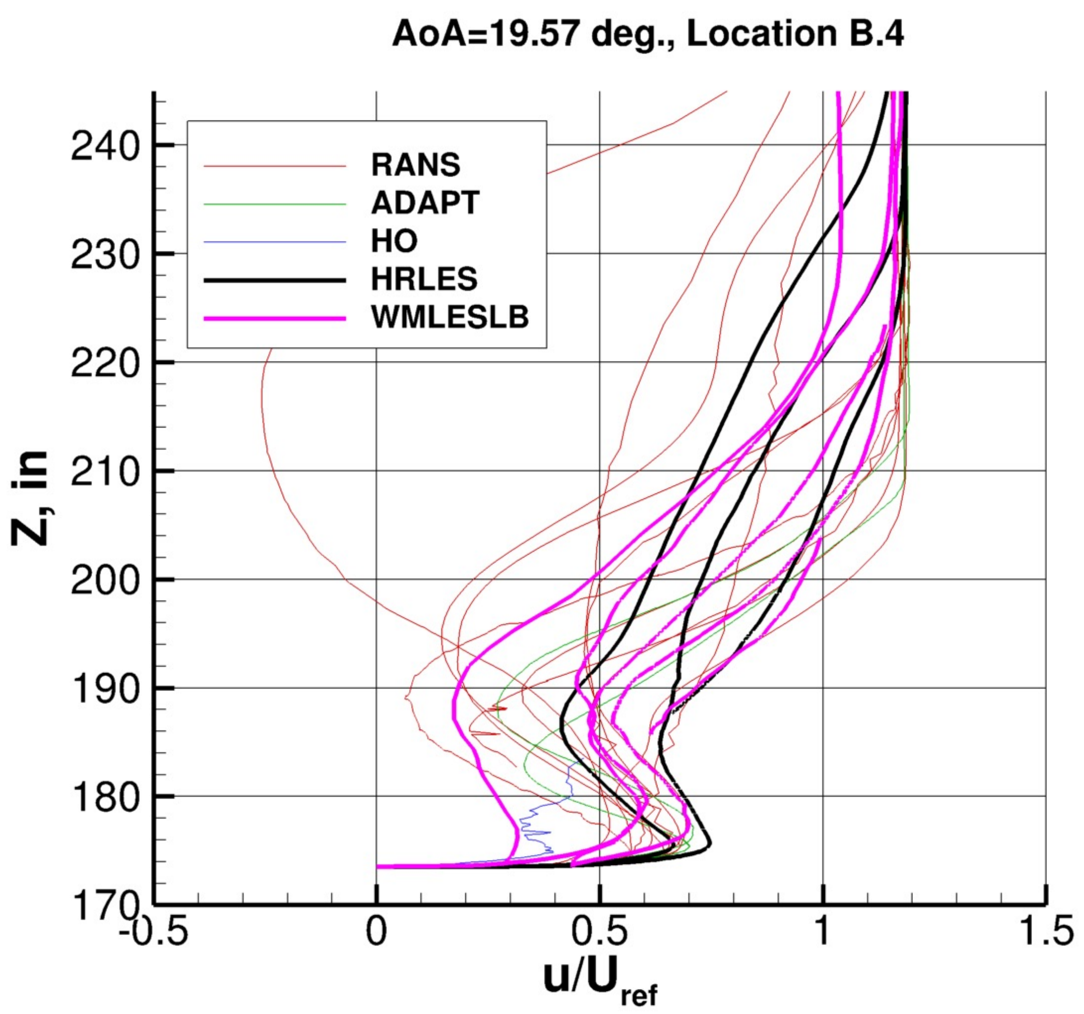


- No clear trends

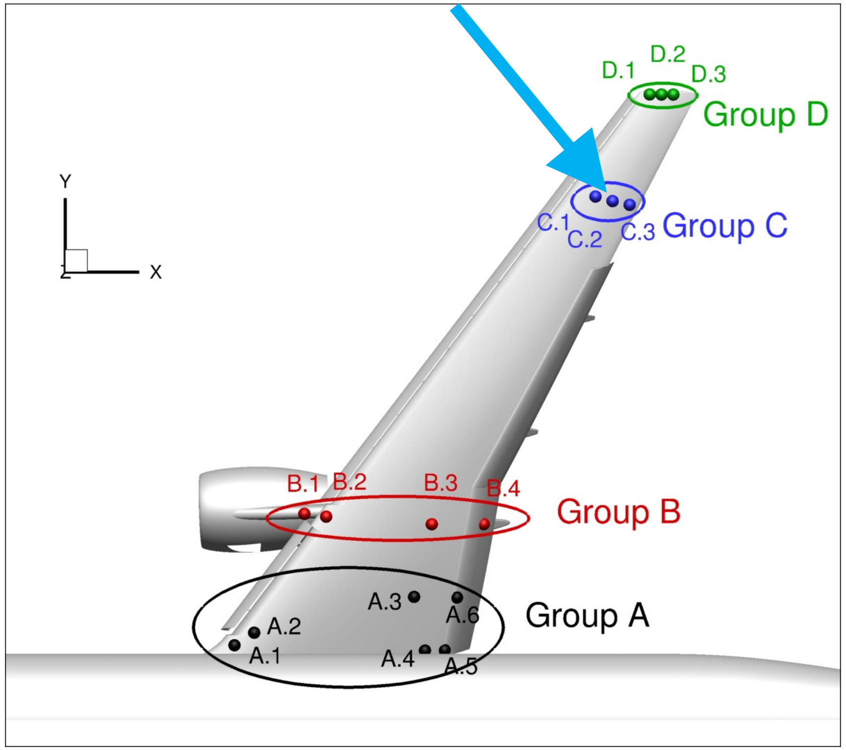
Looking for Trends in Velocity Profiles

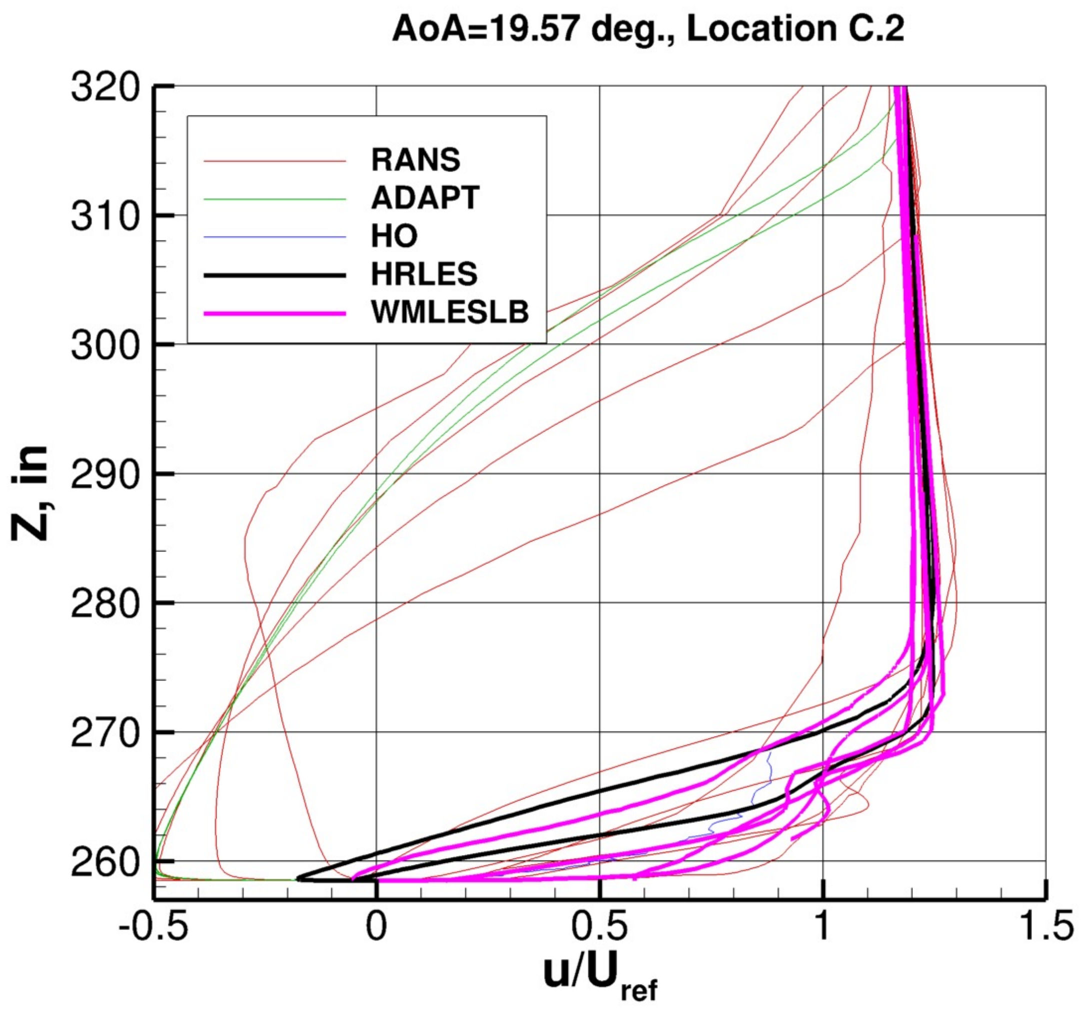


- No clear trends



Looking for Trends in Velocity Profiles





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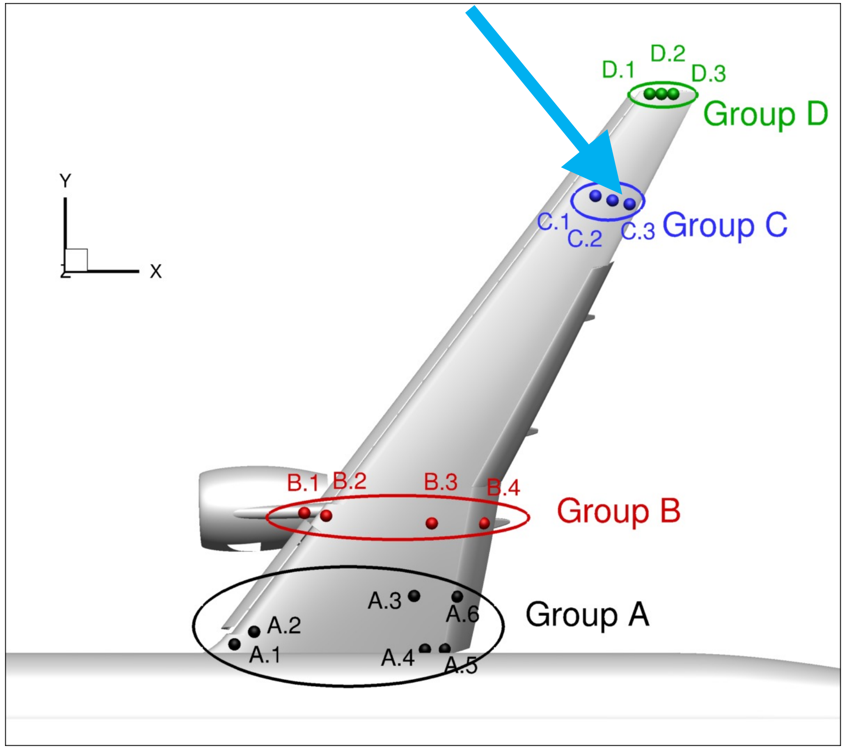
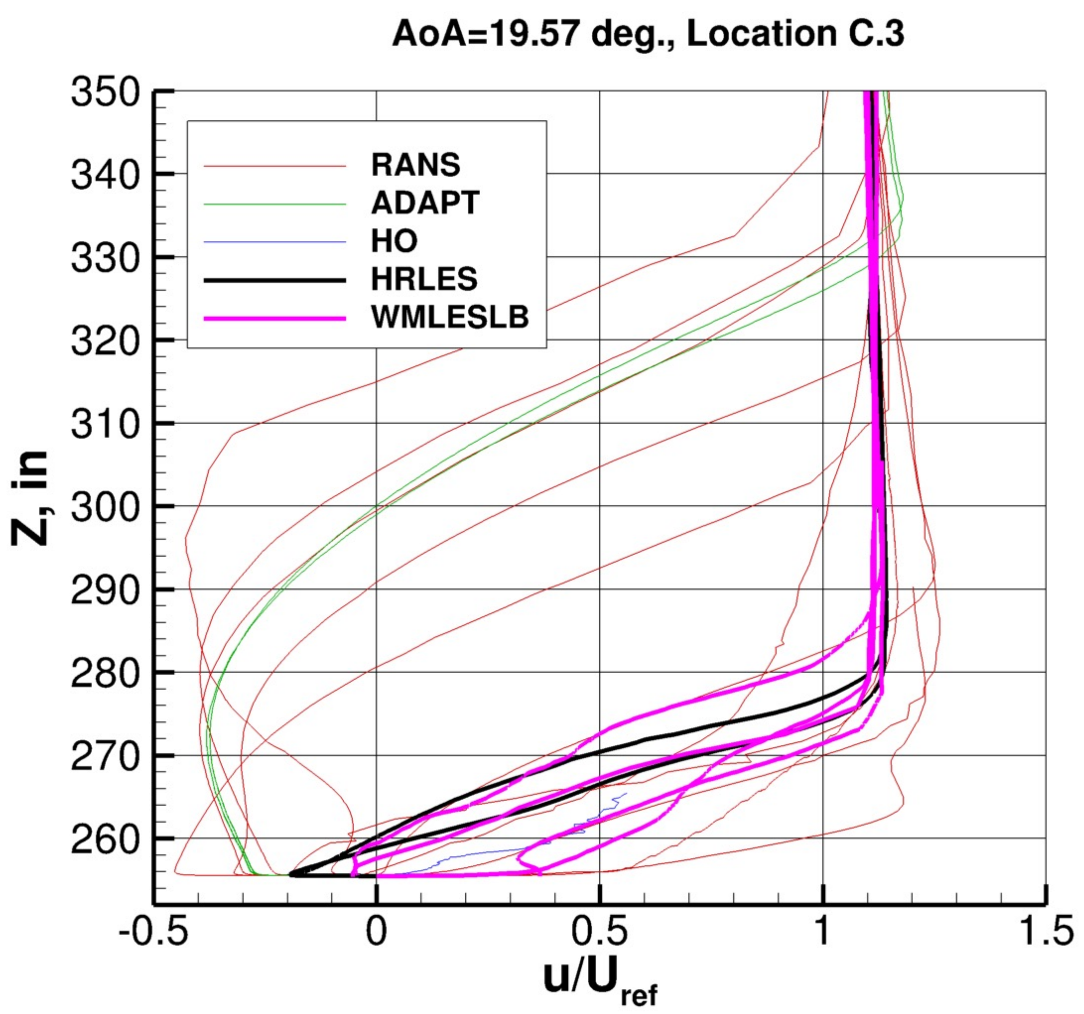
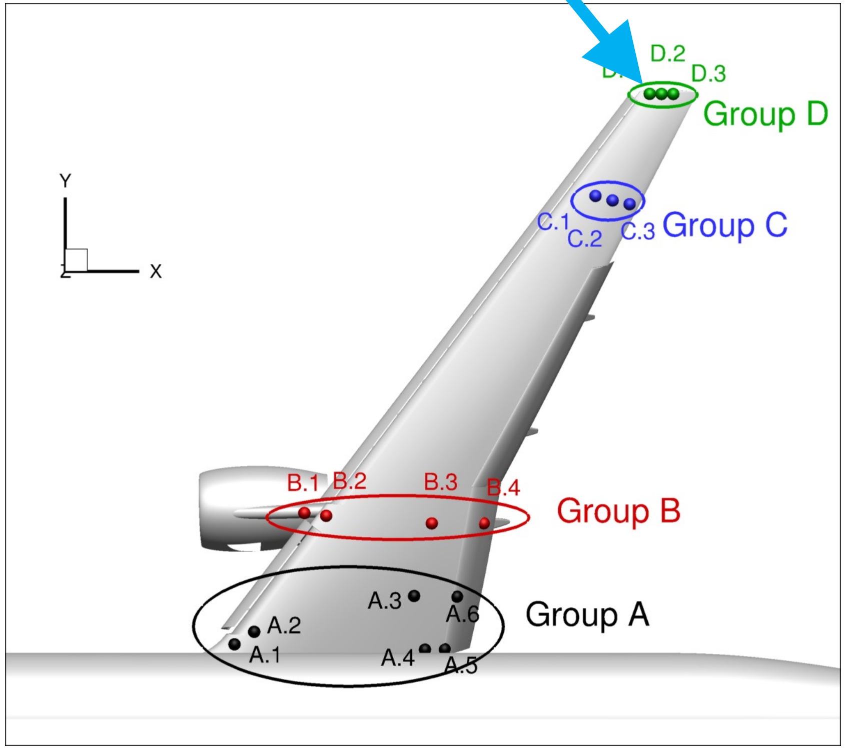
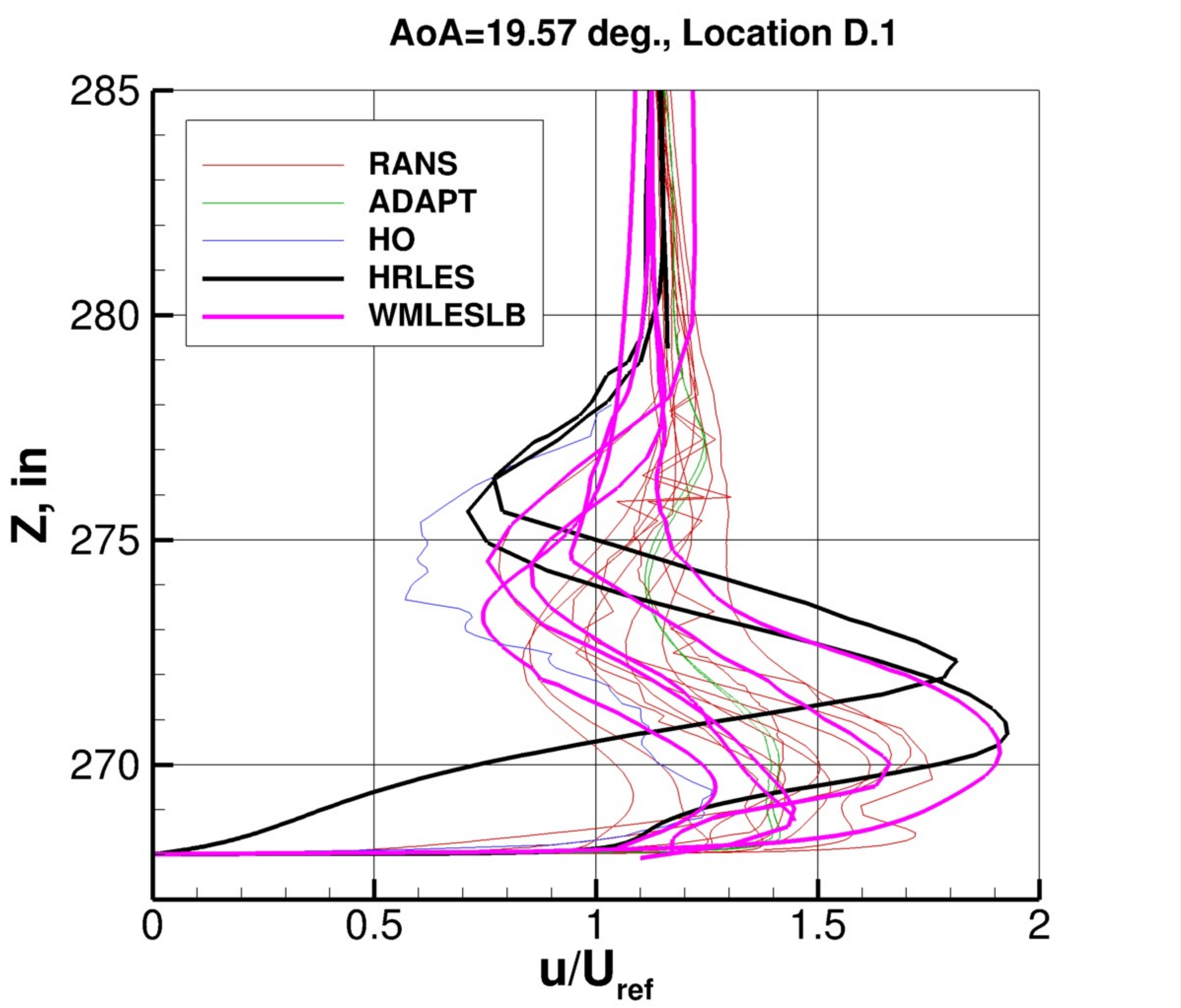




- No clear trends

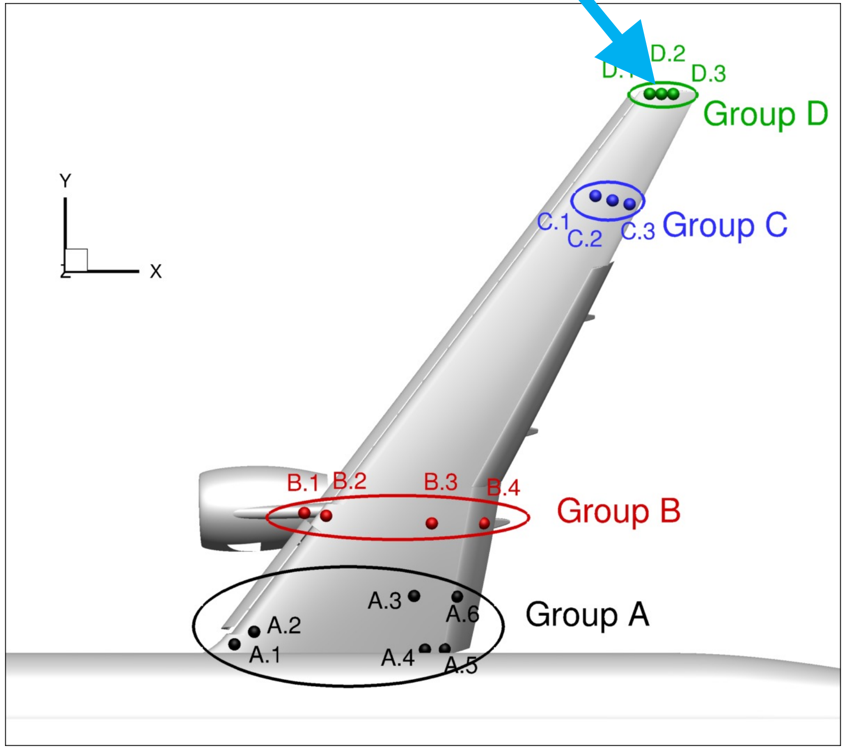
Looking for Trends in Velocity Profiles

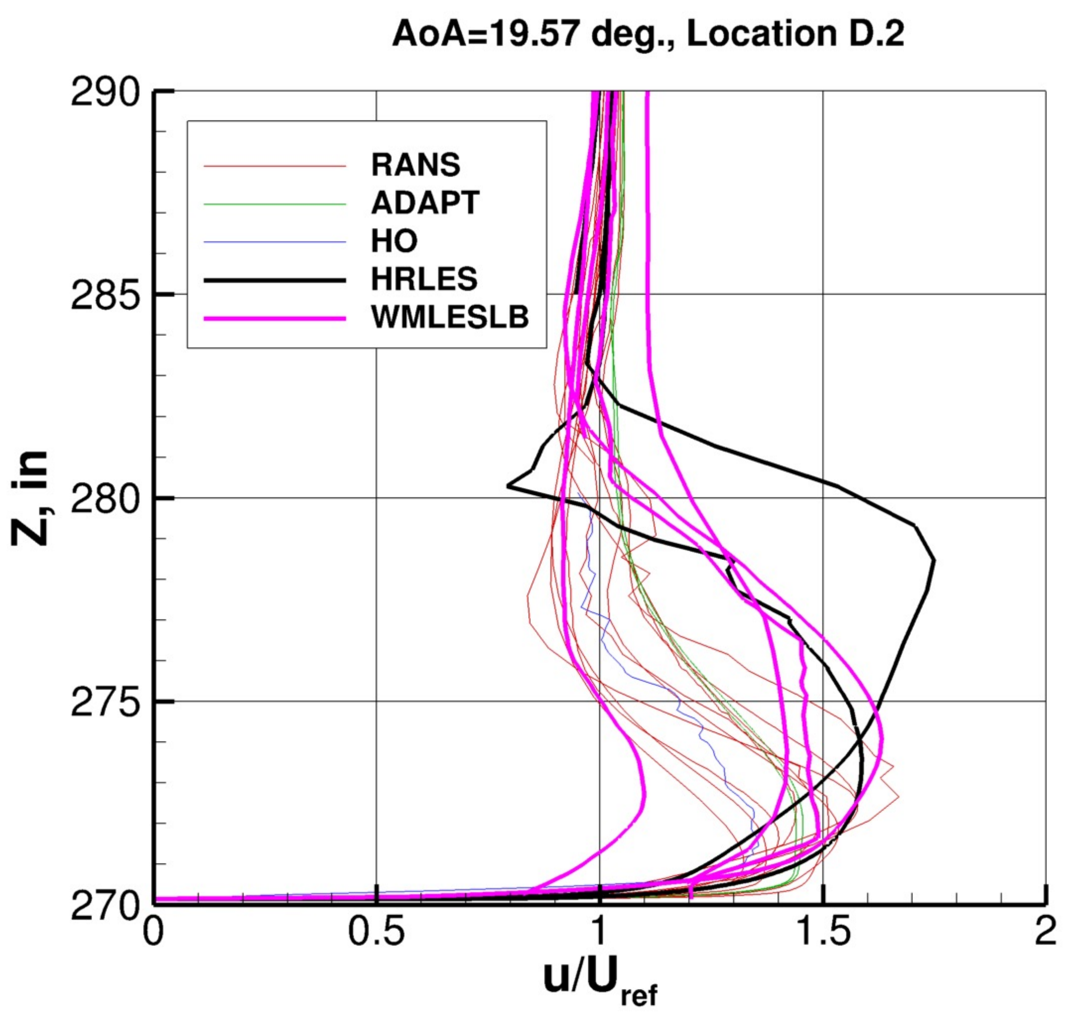




- No clear trends

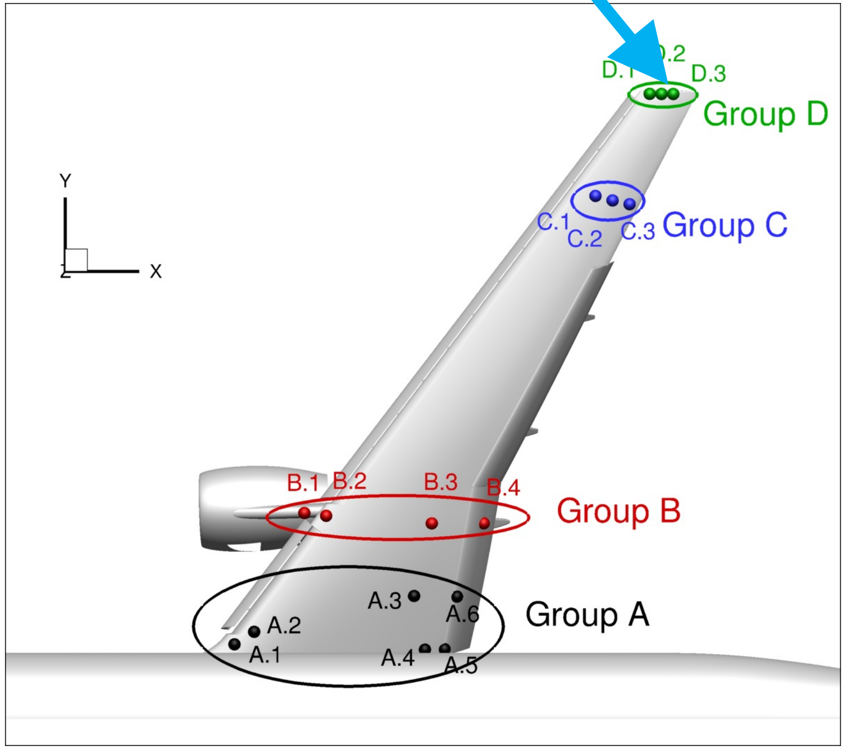
Looking for Trends in Velocity Profiles

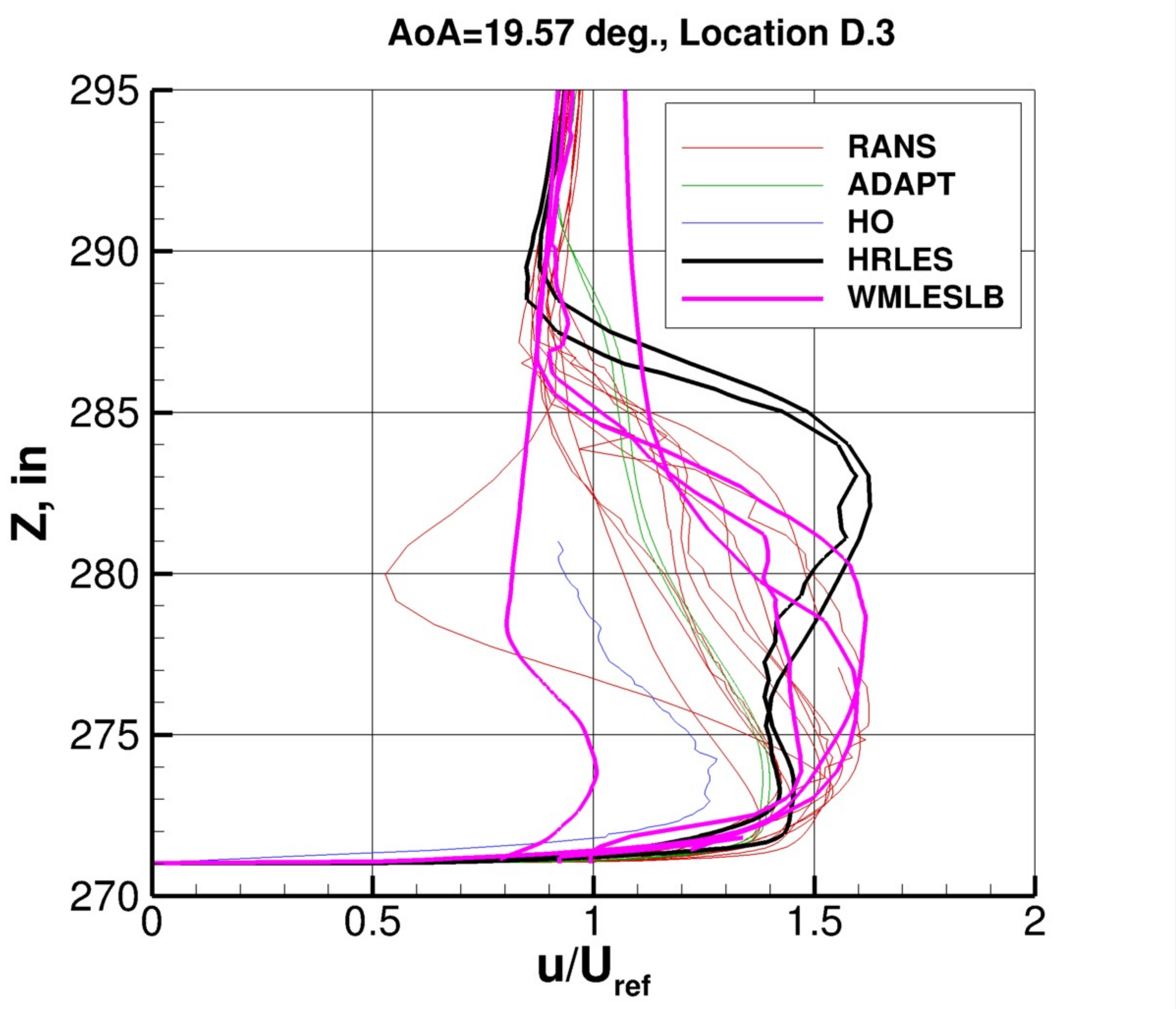




- No clear trends

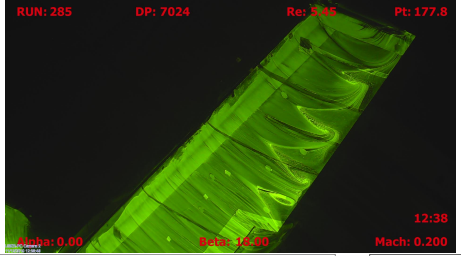
Looking for Trends in Velocity Profiles

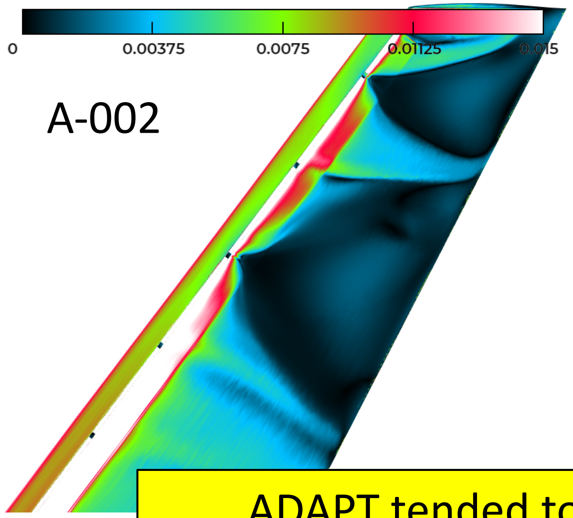


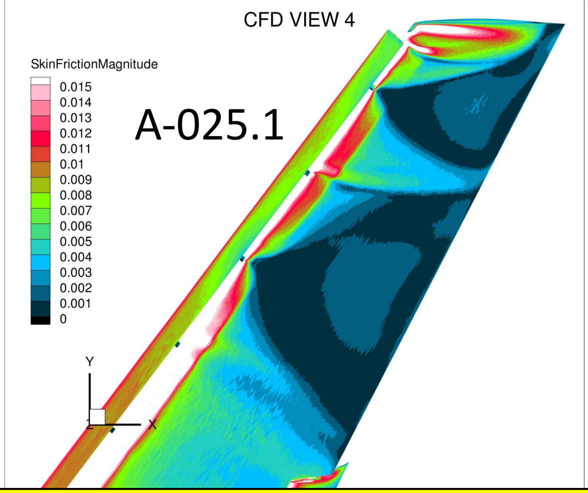


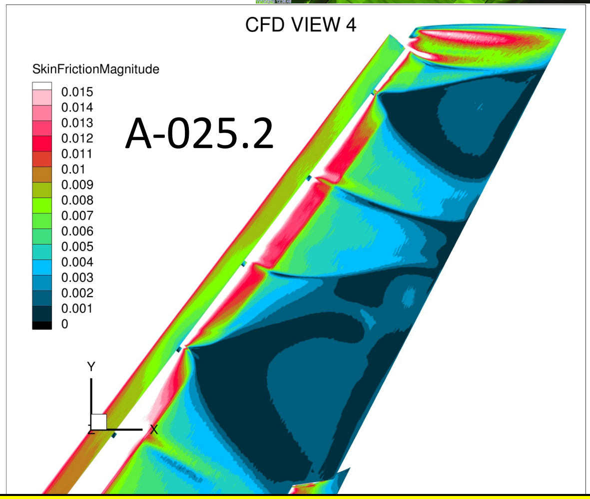
- No clear trends

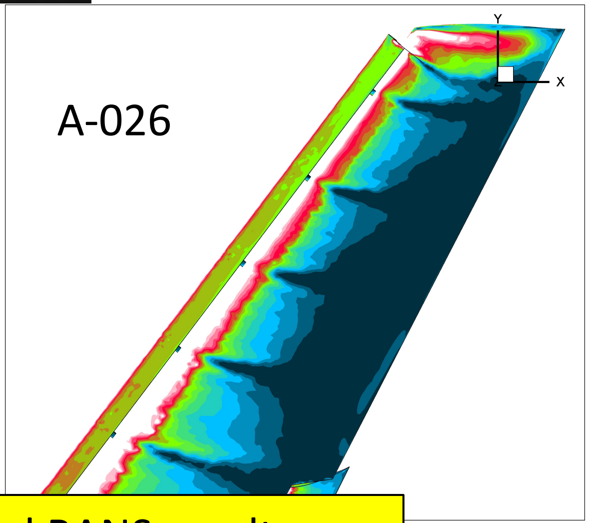
Accuracy at AoA=19.57 deg.



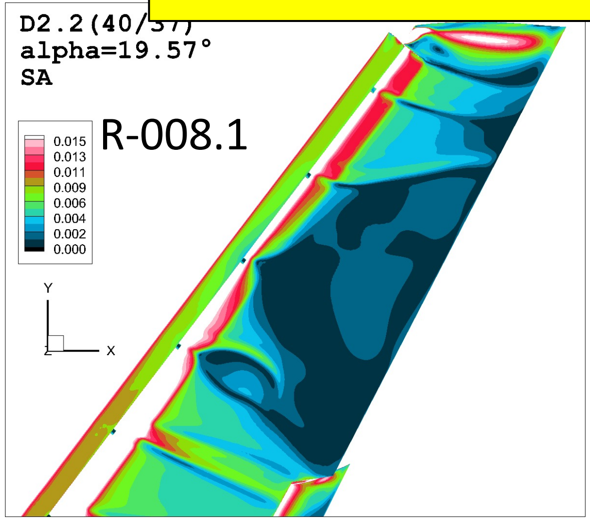


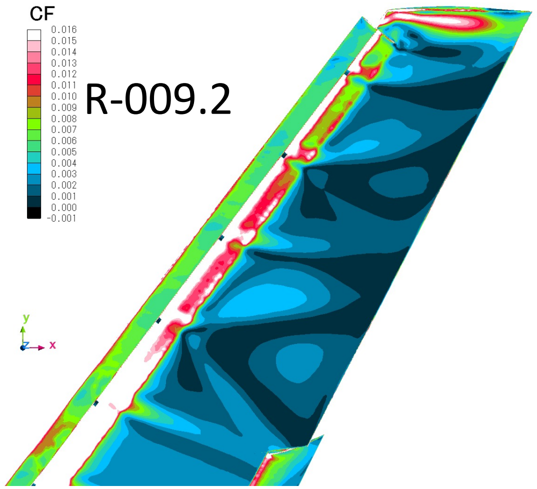


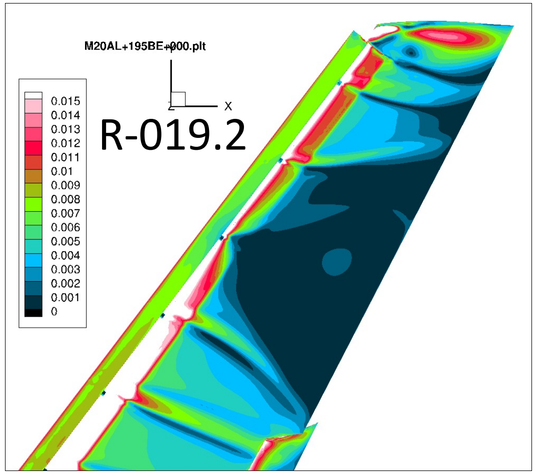


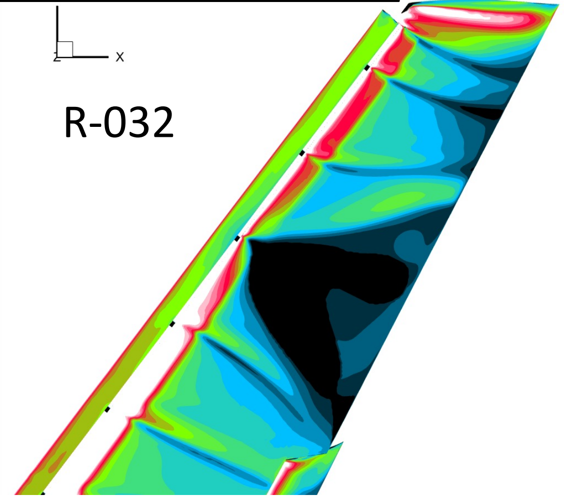


ADAPT tended to have larger outboard separation patterns, like most non-adapted RANS results

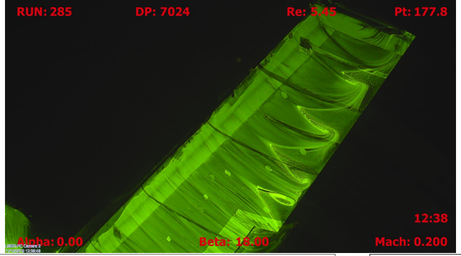


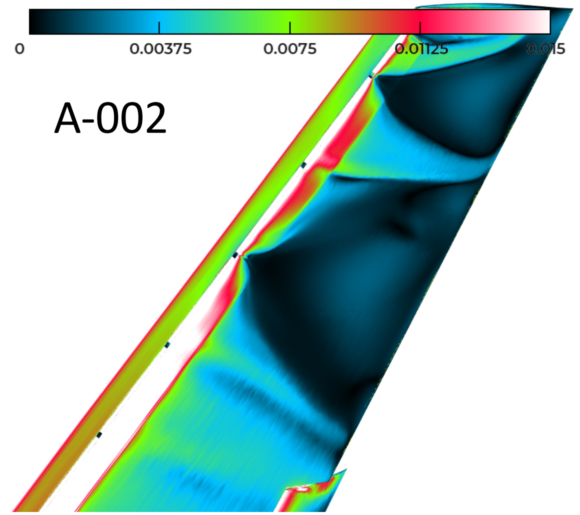


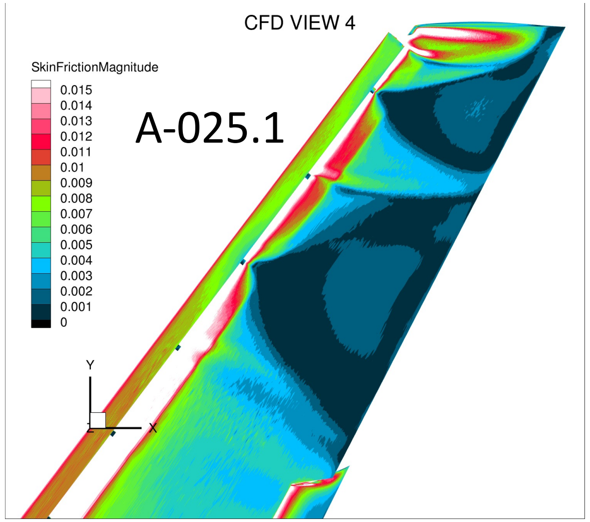


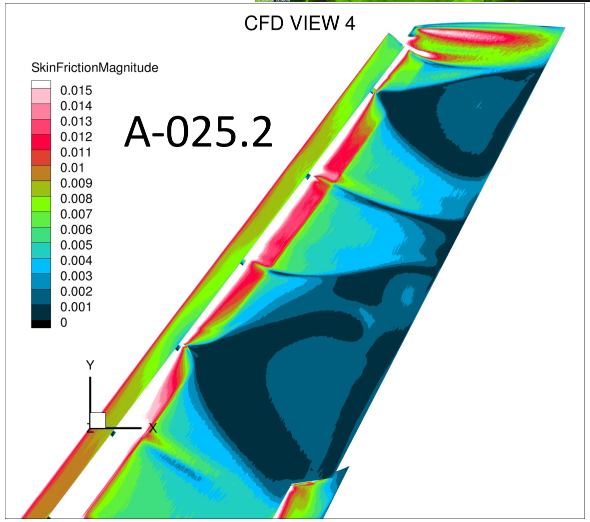


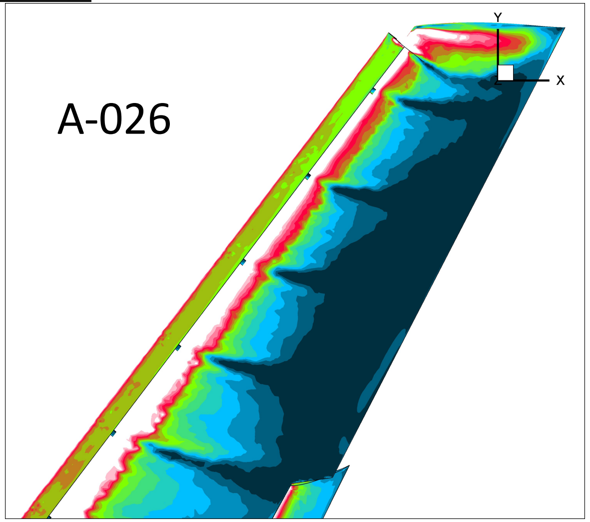
Accuracy at AoA=19.57 deg.

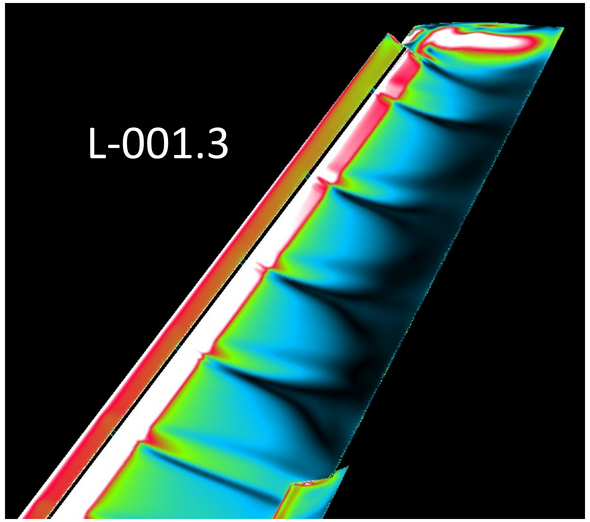


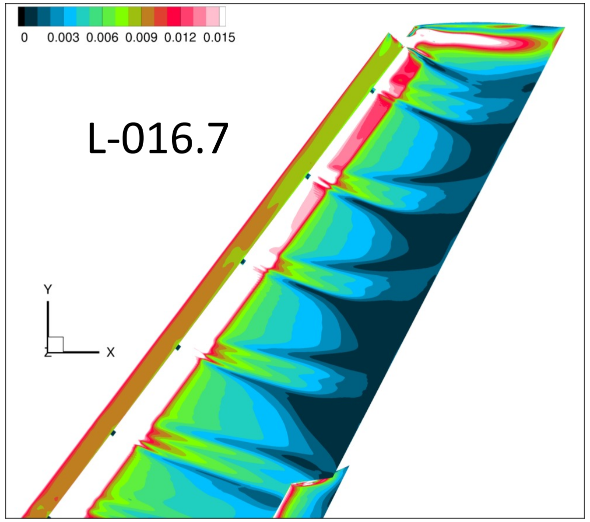


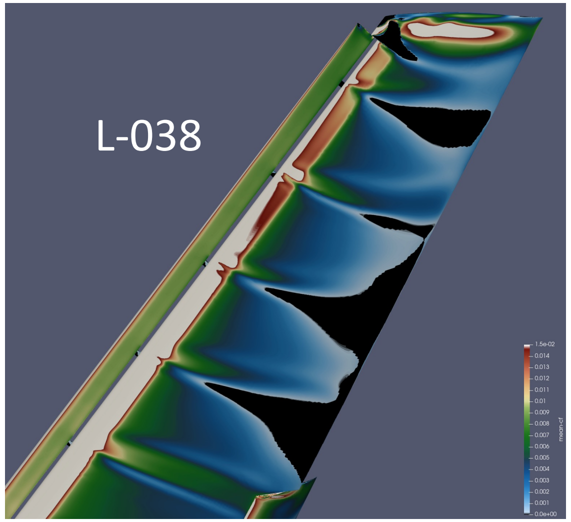












HRLES solutions had less outboard separation than ADAPT solutions

Accuracy at AoA=19.57 deg.